POLITECNICO DI TORINO

SCUOLA DI DOTTORATO
Dottorato in Ingegneria Aerospaziale - XXV ciclo
SSD ING-IND/05 - Impianti e sistemi aerospaziali

Tesi di Dottorato

Sistemi Multifunzionali Integrati

Quattro prototipi che affrontano aspetti termici, elettrici e controllistici.

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Tutore aziendale
Thales Alenia Space
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Tesi di Dottorato

Integrated Multifunctional Systems

Four prototypes including thermal, electrical and control aspects.

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Abstract

Questa tesi è nata nel contesto di una attività di ricerca condotta da Thales Alenia Space Italia e chiamata *Integrated Multifunctional Systems*. Il nome è abbastanza auto-esplicativo: la ricerca ha riguardato lo studio di sistemi integrati multifunzionali. In particolare, il lavoro di seguito descritto ha preso in considerazione sistemi multifunzione che combinano aspetti termici, strutturali, di funzionalità elettrica ed elettronica e di controllo.

La motivazione fondamentale per questa attività deriva da un'attenta valutazione dei driver di missione e dei vincoli ai quali è assoggettato il progetto dei sistemi spaziali. Negli ultimi 30 anni, interessanti studi statistici [1] hanno analizzato un nutrito campione di veicoli spaziali per estrarre informazioni sulla composizione della *dry mass* totale, chiamata anche massa a vuoto, ovvero la massa del veicolo meno le masse di propellenti ed altri fluidi o liquidi (pressurizzanti, refrigeranti. . .). Questi studi hanno dimostrato che i maggiori contribuenti della massa a vuoto sono due campi disciplinari: struttura ed elettronica. Questo risultato indica una promettente area aperta allo sviluppo tecnologico, che potrebbe portare ad una significativa riduzione della massa dei veicoli spaziali.

Possibili aree di interesse da affrontare nella ricerca sono: introduzione di nuove architetture di bus, uso di nuovi packaging o configurazioni per l'elettronica, ideazione di telai elettronici che funzionino anche come elementi strutturali, minimizzazione dei cablaggi. In aggiunta c'è un interesse sempre maggiore per la distribuzione impercettibile di componentistica per il controllo termico ed il monitoraggio della struttura. La sfida è quella di soddisfare le contrastanti esigenze di missione tenendo in conto una progettazione integrata che affronta contemporaneamente tutti questi settori: supporto strutturale, funzionalità elettrica, packaging dei componenti ed elementi termici.

In particolare, per questa tesi, l'obiettivo era quello di identificare differenti modi di combinare funzioni elettriche, elettroniche e di controllo termico con strutture meccaniche, in modo da creare un sistema multifunzionale in grado di ridurre masse e volumi a parità di prestazioni e semplificare l'integrazione del prodotto finito. Lo scopo del lavoro è stato quello di selezionare materiali e tecnologie da utilizzare nelle aree precedentemente citate (elementi strutturali, soluzioni termiche, elettronica integrata. . .), di ideare, progettare e produrre prototipi dimostrativi idonei, e di valutare l'applicazione di tecniche di progetto ed ottimizzazione multidisciplinari in questo campo.

Il lavoro è stato condotto in stretta collaborazione con Thales Alenia Space Italia SpA (TAS-I), e con il Jet Propulsion Laboratory (JPL) / California Institute of Technology (Caltech). Su di un periodo di tre anni, quattro differenti dimostratori tecnologici sono stati considerati: tre di essi sono stati sviluppati con TAS-I, ed uno con il JPL. In ordine cronologico, il primo prototipo è l'Advanced Bread Board (ABB), che è un pannello termostrutturale costruito in Carbon/Carbon ed equipaggiato con elettronica e sensoristica distribuita. Il secondo prototipo è stato realizzato in tre differenti varianti: SDA, SDB, e SDC (rispettivamente, STEPS Demonstrator A, B, e C). Si tratta di una motherboard intelligente, modulare, e flessibile che è stata montata su di un pannello sandwich in alluminio, su di una piastra curva sempre in alluminio e su di uno strato di tessuto di Kevlar. Il terzo prototipo, che è uno sviluppo del concetto introdotto con STEPS, è attualmente in fase di studio all'interno del Programma di ricerca europeo ROV-E: consiste in una *smart skin*, ovvero una pellicola intelligente che può essere applicata su qualsiasi supporto ed integra in un unico strato elettronica, cablaggi, sensoristica e riscaldatori. Il quarto prototipo è il micro rover sviluppato presso il JPL: un piccolo robot a quattro ruote realizzato integralmente con circuiti stampati (PCB) termostrutturali.

I quattro prototipi rappresentano fasi successive verso la realizzazione di un sistema multifunzionale dove l'elettronica, in configurazione flessibile o rigido-flessibile, forma un unicum con la struttura. L'obiettivo è quello di realizzare un'architettura distribuita, dotata di intelligenza sufficiente per gestire la comunicazione, il controllo termico ed ambientale, e l'azionamento di utenze. ABB è il primo esempio, in cui le piccole schede flessibili dotate di limitata intelligenza sono montate su di un substrato strutturale con elevate prestazioni termomeccaniche. Dopo i risultati ottenuti da ABB, il filone di ricerca è stato idealmente suddiviso in due rami.

Il primo ramo di studio rimane fissato sullo sviluppo di elettronica flessibile in grado di integrare le capacità di comunicazione, health monitoring, cablaggi di segnale e di potenza, ed allo stesso tempo di adattarsi all'applicazione su molti materiali differenti di supporto. I dimostratori STEPS e la *smart skin* di ROV-E sono prodotti provenienti da questo approccio. I primi mostrano maggiori dimensioni, funzionalità più estese, e più alto livello di intelligenza a bordo rispetto ad ABB. La *smart skin* di ROV-E porta queste stesse caratteristiche alla loro massima estensione: il design si concentra su una scheda estremamente flessibile, in grado di monitorare la struttura e l'ambiente circostante, di azionare carichi e di prendersi cura della distribuzione di segnale e di energia.

D'altra parte, il secondo ramo di ricerca esplora la possibilità di utilizzare le schede elettroniche stesse (in configurazione rigido-flessibile) come elementi strutturali: il micro rover progettato per il JPL è il prodotto di questo approccio. Il piccolo robot ha lo scopo di mostrare la fattibilità ed il vantaggio nell'eliminare le tradizionali scatole elettroniche trasferendo tutti i componenti sulla struttura primaria, che viene quindi realizzata con circuiti stampati basati su particolari materiali termostrutturali.

Tutti i punti di cui sopra sono stati sviluppati nel corso dei tre anni di lavoro, ma è importante riconoscere il contributo di diverse persone che hanno dato un sostegno fondamentale per raggiungere l'obiettivo finale. Innanzi tutto un grande merito va attribuito ai colleghi in TAS-I ed al JPL, che hanno contribuito a risolvere i problemi di progetto e ad individuare la giusta direzione per le attività. Non meno essenziali sono stati i tutor ed i colleghi dottorandi, che hanno condiviso le loro idee ed i loro suggerimenti. Altrettanto importanti sono stati gli studenti che hanno curato parte delle attività di modellizzazione ed analisi come argomento della loro tesi di laurea. Non meno degno di nota è stato il ruolo dei consulenti e dei fornitori delle varie aziende coinvolte nella realizzazione dei dimostratori tecnologici: essi hanno dato preziosi consigli sulla fattibilità tecnica del progetto ed hanno materialmente costruito i prototipi.

Questa tesi descrive il lavoro svolto dal 2010 al 2012 per lo sviluppo dei sistemi integrati multifunzionali, ed è divisa in cinque capitoli principali, introdotti da una prefazione. Tale prefazione presenta il tema e gli obiettivi del lavoro e descrive la metodologia di ricerca utilizzata durante le attività. Essa descrive anche la struttura della tesi e riconosce i contributi fondamentali.

Il primo capitolo è dedicato ad un esame della letteratura disponibile. Il suo obiettivo è quello di esplorare lo stato dell'arte, per raccogliere e riassumere informazioni su attività che sono state effettuate fino ad oggi nel campo dei sistemi multifunzione. Queste attività sono le fondamenta su cui il lavoro descritto in questa tesi è stato costruito e rappresentano il punto di riferimento per la valutazione dei risultati conseguiti. Pertanto, è stata anche inclusa una sezione che contiene un'analisi critica delle attività più strettamente inerenti questa tesi.

Il secondo capitolo descrive come la ricerca sia stata effettivamente svolta, lo studio delle varie tecnologie, l'attività di progetto, l'effettiva implementazione del design, la descrizione tecnica di tutti i diversi prototipi, ed un primo accenno ai risultati ottenuti.

Il terzo capitolo presenta in dettaglio il lavoro di analisi multidisciplinare e di test. I risultati di queste attività sono discussi nel quarto capitolo, che si propone anche di discutere la loro posizione nel contesto degli obiettivi iniziali e/o della letteratura disponibile.

Il quinto capitolo riassume i punti salienti, trae le conclusioni e spiega dove è necessario un ulteriore lavoro e quali sono le attività attualmente in corso per trasferire la tecnologia dei sistemi multifunzionali dal laboratorio al veicolo spaziale.

Per ampliare la discussione su alcuni argomenti accennati all'interno del testo principale, o per offrire informazioni aggiuntive su specifiche tecnologie, è stata aggiunta un'appendice.

Le attività descritte in questa tesi hanno risposto a tutti gli obiettivi inizialmente fissati.

Il primo obiettivo era quello di completare il lavoro sul dimostratore ABB, con la sua integrazione e le attività di test. Il prototipo è stato giustappunto completato ed è stato sottoposto ad una campagna di prove in termovuoto, che ha portato ad una valutazione positiva della tecnologia MFS.

Un secondo obiettivo è stato quello di sviluppare la ricerca sul multifunzionale per il progetto STEPS, dalla fase di design, alla costruzione ed alla verifica dei prototipi. I tre dimostratori STEPS sono stati effettivamente progettati, costruiti e testati, sia in condizioni ambiente che in termovuoto. Questi test hanno dimostrato la funzionalità del design ed evidenziato aree in cui lo studio può essere ulteriormente migliorato.

Un terzo obiettivo è stato quello di cercare nuove opportunità per espandere la ricerca nel campo dei sistemi multifunzionali. Questo obiettivo è stato perseguito da un lato con l'acquisizione di un nuovo finanziamento sotto il settimo Programma Quadro della Commissione Europea, che ha quindi dato inizio al programma ROV-

E, e dall'altro con lo sviluppo di uno studio affine in collaborazione con il Jet Propulsion Laboratory. Le attività svolte per ROV-E hanno portato al progetto preliminare di una *smart skin* migliorata, mentre e il lavoro condotto per il JPL ha dato l'opportunità di progettare un piccolo dimostratore di rover basato su MFS e di costruire un mock-up intermedio.

Un quarto obiettivo era quello di introdurre un approccio multidisciplinare per la progettazione e l'analisi dei sistemi multifunzione. La MDO è stata studiata e poi applicata, dapprima per due *loop* di dimostrazione che hanno avuto come casi di studio ABB ed un prototipo STEPS, e poi per un re-engineering del design di ABB. Questo ultimo studio ha dato risultati interessanti, che sono stati incorporati come linee guida nel progetto ROV-E.

Le aree tecnologiche selezionate per essere esplorate con questa tesi erano: circuiteria flessibile con dispositivi integrati intelligenti, hardware termico incorporato, sistemi di diagnostica e controllo distribuito, strutture in carbonio con alta conducibilità termica e buone caratteristiche meccaniche. Tutti questi argomenti sono stati studiati e fatti convergere nel progetto dei tre più recenti dimostratori di sistemi multifunzionali sviluppati da Thales Alenia Space Italia e JPL.

Per quanto riguarda l'approccio MFS in generale, i prototipi sono riusciti a dimostrare la fattibilità di due concetti differenti, che possono essere declinati in varie modalità per creare un sistema distribuito con le seguenti caratteristiche:

- Riduzione del numero di I/O e dei sistemi di cablaggio tradizionali: l'approccio basato su *smart skin* elimina una grande quantità di collegamenti e connettori, sostituendoli con un unico nastro sottile o incorporandoli in una scheda madre.
- Creazione di un layout modulare, flessibile o rigido-flessibile, che può adattarsi a diverse applicazioni, architetture e configurazioni, dai satelliti per telecomunicazioni, ai veicoli di esplorazione, ai moduli abitati "gonfiabili" .
- Distribuzione dell'elettronica sulla struttura di supporto, liberando volume che precedentemente era allocato per supporti ed involucri metallici e riducendo la massa rispetto ad una equivalente scheda madre tradizionale rigida.
- Distribuzione di dispositivi intelligenti, con capacità di calcolo e di controllo, su tutto il sistema, invece di centralizzare tali funzioni in un'unica area.
- Inclusione di soluzioni di gestione termica, che possono andare dalla presenza passiva di un materiale dotato di elevata conducibilità, fino all'incorporazione di riscaldatori pilotati da una logica di controllo responsabile della loro attuazione.

I due concetti sopra menzionati sono la *smart skin*, scheda elettronica piatta, sottile, intelligente e modulare, ed i sistemi basati su PCB in cui schede elettroniche ripiegabili assolvono anche compiti strutturali.

Parlando della *smart skin*, una vera svolta è stato il cambiamento di paradigma avuto nel passaggio da soluzioni multifunzionali massicce verso un prodotto molto sottile e leggero, che può installare funzionalità aggiuntive su di una varietà di strutture, portando con sé solo una minima penalità in massa. In particolare, l'uso di substrati flessibili polimerici può consentire la fabbricazione di dispositivi con un processo reel-to-reel, un metodo di produzione ad alto volume e bassi costi. Vale anche la pena ricordare che tali materiali e metodi di produzione possono aprire nuove opportunità per il progettista, perché sono intrinsecamente adatti per favorire applicazioni atipiche, come l'elettronica stampata a getto d'inchiostro o in serigrafia. Sotto questo punto di vista, il concetto di *smart skin* attualmente in fase di studio presso Thales Alenia Space Italia è in prima linea nella ricerca sugli MFS e non ha eguali in letteratura. Da studi pubblicati negli Stati Uniti si evince che esistono un notevole interesse ed una grande fiducia nelle potenzialità dell'elettronica e della circuiteria flessibile per applicazioni spaziali, ma fino ad ora il suo utilizzo è stato attivamente proposto unicamente in sostituzione dei cablaggi tradizionali [31]. La *smart skin*, invece, è un mezzo per arricchire una struttura tramite l'aggiunta di diverse caratteristiche: componenti elettronici distribuiti installati in superficie con tecnologia SMD, reti di sensori per il rilevamento dello stato di sollecitazione del sistema, funzioni di controllo, circuiteria piatta, flessibile e modulare che fornisce interconnessioni con minimo ingombro e riscaldatori integrati per consentire il controllo termico.

Allo stesso tempo, anche l'elettronica strutturale ripiegabile studiata al JPL è una soluzione piuttosto nuova, nel senso che fino ad ora sono state effettuate prove per laminare e nidificare l'elettronica all'interno di componenti strutturali, ma non c'è invece alcun esempio funzionante dell'utilizzo di circuiti stampati come componenti strutturali per applicazioni spaziali[1].

In entrambi i casi, questi concetti di sistema multifunzionale tendono a minimizzare il numero di componenti, ridurre la massa ed il fattore di forma (volume), mentre allo stesso tempo cercano di massimizzare l'efficienza di input/output e migliorare affidabilità e producibilità dei circuiti. In particolare, sotto questo ultimo punto di vista, è interessante notare che tutti i prototipi considerati in questa tesi sono immediatamente realizzabili con gli attuali materiali, macchine e utensili utilizzati nell'industria dei PCB. Inoltre, anche l'idea di avere un prodotto modulare è di grande interesse, soprattutto allorché è possibile "depopolare" il design di riferimento al fine di ridurre il numero di sensori e riscaldatori installati, senza necessità di rilavorazione o variazione del progetto della scheda madre base. Ciò consente una economica distribuzione delle capacità di monitoraggio e controllo su superfici molto ampie. L'architettura modulare è molto utile anche per affrontare il problema della rilavorazione o riparazione. Nella concezione iniziale di struttura multifunzionale, incarnata in ABB, l'approccio adottato per consentire di correggere le anomalie ed eseguire rilavorazioni o riparazioni è stato quello di includere incastellature tridimensionali. Questi agganci e montaggi tenevano in posizione i componenti che avrebbero potuto essere smontati e sostituiti. Tuttavia, questa idea era in conflitto con l'obiettivo di avere un singolo strato flessibile. Quindi il design è stato indirizzato verso l'adozione di piccoli moduli intercambiabili che possono essere facilmente sostituiti. In questo modo, è possibile testare ogni modulo e, in caso di anomalia, scartarlo prima della sua installazione. Solo moduli controllati e preselezionati,

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[1] Per completezza è bene citare che interessanti studi sono stati condotti sulla stampa diretta di circuiti elettronici su elementi strutturali in campo UAV e recentissimamente, proprio in questi ultimi mesi, il concetto si sta spostando verso il settore spaziale [86]. In realtà, questa è anche una potenziale evoluzione futura del ramo di ricerca del JPL, che sta procedendo verso un approccio "printed spacecraft" .

privi di difetti, vengono dunque integrati sul veicolo. Inoltre, ispirandosi alle buone pratiche di progetto e sviluppo, tracce conduttive addizionali, dotate di piazzole aperte, possono essere distribuite su tutto il modulo con la differenza che, in questo caso, non sarebbero utilizzate per correggere errori di design, bensì per consentire un intervento veloce in caso di guasto (ad esempio, sarebbe immediato creare ponticelli a saldare per aggirare aree danneggiate od interruzioni intenzionali dei conduttori). Infatti, l'esperienza acquisita durante il test termovuoto dei prototipi STEPS, ha dimostrato che i moduli *smart skin* garantiscono una ispezione ed una rilavorazione piuttosto agevoli al fine di risolvere eventuali problemi, anche dopo che sono già stati incollati al loro substrato definitivo. In particolare, è stato possibile ispezionare e riparare le *smart skin* montate su SDA ed SDB senza la necessità di staccarle dal loro supporto (al contrario, con un tradizionale circuito stampato, il procedimento avrebbe comportato la rimozione ed apertura di un involucro metallico, per poi passare all'estrazione meccanica del componente difettoso).

È importante sottolineare il fatto che, durante l'attività di ricerca per lo sviluppo della *smart skin* STEPS, l'attenzione era effettivamente focalizzata sul singolo modulo flessibile, per sviluppare la sua architettura e le sue caratteristiche, e non su di un sistema completo con un gran numero di esemplari interconnessi. Per queste ragioni, durante l'integrazione dei dimostratori finali, sono stati usati cavi twistati dedicati per collegare i vari moduli. Tuttavia, la realizzazione del concetto MFS di TAS-I ha sempre presupposto un sostanziale alleggerimento delle attività di integrazione e di assemblaggio che si rendano ancora necessarie nonostante l'applicazione della *smart skin*, che riduce notevolmente gli I/O e l'onere di lavorazione. Per questo motivo, la presenza di cavi di interconnessione a nastro flessibile, terminato con estremità rinforzate atte ad essere inserite in connettori a bassa o nulla forza di inserzione, è una componente fondamentale della *smart skin* ROV-E. Questa soluzione è l'approccio migliore per ridurre al minimo le attività di intervento manuale sul cablaggio ed al tempo stesso ridurre l'incidenza dell'errore umano.

Entrando nei dettagli dell'applicazione ABB, il concetto di una rete digitale distribuita di sensori di temperatura si è rivelato utile: può davvero ridurre masse, volumi e costi, in quanto riduce significativamente i cablaggi necessari per il monitoraggio, sulla base del fatto che tutti i vari fili di collegamento sono ridotti ad una piattina flessibile. Tale nastro potrebbe essere utilizzato come una serpentina poco costosa che percorre agevolmente tutto il veicolo spaziale. Inoltre, vi è un grande interesse nel trasferire questa tecnologia al settore che si occupa dei test, poiché una soluzione simile consente una rapida strumentazione del provino, un set-up minimale dell'infrastruttura di laboratorio, ed una semplicissima acquisizione dei dati. I risultati della campagna di test in termovuoto hanno mostrato che l'elettronica flessibile basata su Cu/PI è stata in grado di resistere alla ciclatura termica in vuoto senza subire danni: la procedura di incollaggio al substrato, basata sull'utilizzo di Araldite®AV138M / HV998, si è dimostrata efficace e non ha presentato degrado, anche dopo un forte stress termico. Inoltre, l'utilizzo di elettronica COTS non ha minimamente ridotto la funzionalità della scheda madre ed apre quindi interessanti prospettive in tre direzioni:

- Può essere una soluzione semplice ed economica per il collaudo di strutture spaziali, giustificando la transizione verso un monitoraggio diretto in digitale del sistema.

- Può sostituire i tradizionali componenti qualificati ad uso spazio in applicazioni di nicchia come nano satelliti universitari, payload di ricerca, e strumentazione sacrificale per monitoraggio supplementare (come ad esempio i sensori dell'heat shield di Exomars). In alcuni casi potrebbe rappresentare una ridondanza od un ampliamento economico ad una rete di monitoraggio preesistente.
- Può aiutare a preparare il terreno per la qualificazione per uso spaziale di tecnologie commerciali, in primis protocolli di comunicazione a basso numero di fili e la relativa componentistica, che sono molto diffusi nel settore civile, dove hanno già dimostrato buone affidabilità e versatilità.

Il concetto di utilizzare strutture in Carbon/Carbon come pannelli di supporto presentava interessanti potenzialità in termini di sfruttamento della conducibilità termica del materiale per soddisfare esigenze di alta dissipazione termica e requisiti strutturali allo stesso tempo. In una certa misura, i risultati della campagna di test sono incoraggianti, poiché campioni di medie dimensioni mostrano tutte le caratteristiche previste, ma purtroppo l'upscaling della tecnologia di produzione non è stato ancora perfezionato. In particolare, la creazione di un incollaggio monolitico tra pelli e core in una struttura sandwich è l'anello debole del processo. A causa di ciò, campioni costruiti su scala industrialmente rilevante hanno una scarsa risposta meccanica e proprietà termiche ridotte rispetto alle loro controparti più piccole. Dato l'esito non completamente soddisfacente di questo studio, TAS-I ha deciso di accantonare la ricerca sul filone delle strutture avanzate e concentrarsi interamente sugli aspetti termici ed elettronici.

Per quanto riguarda il concetto di *smart skin* STEPS, sono stati progettati e realizzati i moduli base flessibili, insieme al loro software di controllo. Tre dimostratori sono stati assemblati e sottoposti a test funzionali in ambiente ed in termovuoto. I test hanno confermato l'idoneità dei substrati elettronici flessibili per l'utilizzo in condizioni di temperatura e pressione estreme. È stato anche possibile verificare il buon comportamento della componentistica distribuita, che permette un percorso termico ridotto verso la superficie radiativa dove avviene la dissipazione, ed un migliore controllo termico del sistema, sfruttando la presenza di riscaldatori su tutta l'area di controllo. Infatti, avere hardware di controllo termico diffuso su una vasta area, consente di indirizzare le azioni di controllo termico alle posizioni più vicine ai componenti che richiedono riscaldamento: questo può contribuire all'eliminazione dell'effetto avverso dell'inerzia termica e quindi ad ottenere un risultato migliore in termini di minor dissipazione (e perciò risparmio energetico), riduzione dei ritardi temporali e controllo più accurato della temperatura (e quindi, potenzialmente, migliore sfruttamento dell'intero range di esercizio dei componenti).

Per quanto riguarda l'applicazione delle tecniche e degli strumenti di analisi ed ottimizzazione multidisciplinare, il lavoro preparatorio fatto con i due *loop* dimostrativi termostrutturali sui dimostratori ABB e STEPS ha dato risultati positivi. Gli studi hanno estratto informazioni utili sul comportamento di differenti algoritmi, hanno evidenziato il grande vantaggio proveniente da un'esplorazione sistematica dello spazio di design, hanno dimostrato la fattibilità di un esame più

minuzioso, approfondito, e veloce delle alternative di progetto, che consente allo stesso tempo all'ingegnere di concentrarsi sulle scelte di alto livello, lasciando i dettagli computazionali alla macchina.

Il caso di studio basato su ABB, una validazione a posteriori del design del prototipo, si è basato sull'introduzione di variazioni nella potenza dissipata dai riscaldatori, nello spessore del core del pannello ed in quello delle due skin. La valutazione della prestazione termica è stata fatta rilevando le temperature in diciassette punti sulla skin superiore ed in un ugual numero di punti sulla skin inferiore, per poi calcolare le differenze e le medie dei valori (tenendo conto in particolare dei valori medi per le due motherboard, per i due convertitori DC/DC, e per l'intero pannello). La performance strutturale è stata stimata sulla base dei massimi spostamenti lungo le tre direzioni x, y, e z. Gli obiettivi erano di mantenere alcune temperature sensibili all'interno di determinati intervalli, ridurre al minimo il delta di temperatura tra le due skin riferito all'intero pannello (quindi massimizzare la capacità di rigettare calore) e ridurre al minimo la deformazione del panello (cioè aumentare la rigidezza). Lo studio ha identificato una soluzione ottimale avente un ridotto spessore del core ed un aumentato spessore delle pelli. Questa attività ha rappresentato un'utile esperienza circa i problemi e le buone pratiche relative alla modellizzazione e simulazione ai fini dell'ottimizzazione multidisciplinare. È stato anche un'occasione per testare tecniche ed algoritmi differenti per l'esplorazione dello spazio di design e per l'ottimizzazione vera e propria. Inoltre ha dimostrato chiaramente come il processo di ottimizzazione multidisciplinare introduca un necessario bilanciamento in presenza di molteplici obiettivi contrastanti. Per inciso, il lavoro ha dato anche una buona dimostrazione della necessità di supervisione umana per compiere scelte ragionate durante il processo MDO. Un altro interessante effetto collaterale dell'attività è che questa ha aiutato l'identificazione e la correzione di errori di modellizzazione.

Successivamente, il caso di studio basato sul dimostratore STEPS SDA, è stato impostato contemporaneamente al progetto del prototipo e con l'intenzione di indirizzare lo stesso. L'esercizio si è basato sulla conoscenza acquisita grazie al precedente esempio. In questo secondo caso, gli obiettivi erano sempre l'ottimizzazione di un piccolo insieme di parametri per soddisfare requisiti termici (in termini di minimizzazione del gradiente ed osservanza di determinati livelli di temperatura) e strutturali (in termini di riduzione di massa e sopravvivenza a carichi derivanti dal lancio). Nella fattispecie gli obiettivi sono: garantire la minor differenza di temperatura possibile tra il punto più caldo e quello più freddo sulla scheda madre (il che rappresenta un basilare tentativo di ridurre il gradiente termico nel piano) mantenendo allo stesso tempo le temperature massime e minime entro intervalli specifici, e ridurre al minimo la massa del pannello, garantendo al contempo una deflessione minima in direzione perpendicolare al piano del pannello. L'attività ha dato risultati ragionevoli, che sono stati utilizzati per indirizzare le scelte di progetto. Sotto il punto di vista delle potenzialità e dei limiti dell'ottimizzazione multidisciplinare, il lavoro è stato molto utile per mettere in evidenza l'influenza sul risultato di ottimizzazione da parte delle preferenze espresse a priori dal progettista. Questo esperimento ha inoltre rafforzato la convinzione che una valutazione circa l'applicabilità e le prestazioni degli algoritmi all'inizio dell'analisi è di fondamentale importanza per la buona riuscita dello studio.

L'attività di re-engineering di ABB ha avuto come scopo quello di indagare l'effetto di ulteriori sviluppi che potrebbero migliorare il progetto di ABB e della sua famiglia di strutture multifunzionali. In particolare, l'obiettivo era di migliorare le prestazioni di controllo termico dello strato esterno funzionale del pannello, al fine sia di ridurre la quantità di energia richiesta, sia di ottenere una più uniforme distribuzione di temperatura nel piano. La letteratura sull'argomento mostra che non ci sono molti articoli pubblicati sul progetto multidisciplinare dei sistemi multifunzionali. Ci sono alcuni lavori recenti relativi al progetto termico di tali sistemi ([52], [53], [54], [55]). I lavori dedicati all'ottimizzazione multi-obiettivo di aspetti termici delle strutture multifunzionali sono ancora più rari e trattano in particolare del trasporto di calore in fase fluida ([56], [57]). Il lettore può anche trovare alcuni esempi sull'ottimizzazione della componente strutturale delle strutture multifunzionali ([58], [59], [60]). Questi sono principalmente studi sull'ottimizzazione topologica di particolari componenti [58] o studi su architetture per il core di strutture sandwich [59]. Alcuni di questi paper hanno anche affrontato le proprietà termiche delle componenti meccaniche [58]. Il lavoro su ABB, invece, ha riguardato l'applicazione dell'ottimizzazione multiobiettivo alla selezione di un layout e di una logica di controllo per l'hardware termico di queste strutture multifunzionali, al fine di minimizzare il consumo di energia e, in misura minore, di garantire una buona distribuzione della temperatura sul piano. Inoltre, il lavoro era anche volto a dare una dimostrazione quantitativa del beneficio ottenibile con una logica di controllo termico PID. Fino ad ora, il controllo termico PID è stato proposto solamente in alcuni casi specifici con un payload molto sensibile ([61], [62], [63]) per soddisfare requisiti di stabilità termica molto stringenti, e non è mai stato ottimizzato come legge di controllo per un intero sistema allo scopo di diminuire il budget di energia.

Al fine di svolgere questa analisi, è stato creato e validato un modello termico affidabile e leggero, basato sull'analogia elettrica, per il prototipo di struttura multifunzionale. Il modello si concentra sulla descrizione dei fenomeni termici ed elettrici, ma lascia da parte considerazioni di carattere strutturale. Esso associa un modello a parametri concentrati tridimensionale con la descrizione matematica di quattro diverse leggi di controllo per l'attivazione dei riscaldatori, vale a dire metodo ON÷OFF, strategia proporzionale, logica proporzionale-integrale-derivativa ed utilizzo di riscaldatori a coefficiente di temperatura positivo. Il modello parametrico è stato dapprima validato e correlato attraverso un confronto con semplici soluzioni fisiche, e quindi con l'effettivo risultato di un test di termovuoto. Questo modello è stato poi utilizzato per eseguire più simulazioni, con parametri che sono stati di volta in volta determinati attraverso tecniche di design of experiment ed algoritmi di ottimizzazione multiobiettivo.

I tre studi di ottimizzazione (basati su algoritmi genetici) hanno avuto l'obiettivo di stabilire le migliori configurazioni di layout degli heater, individuare la migliore strategia di controllo, sia in termini di isotermia del pannello che in termini di consumo di energia, ed in conclusione affinare i parametri relativi alla migliore strategia di controllo termico selezionata. La valutazione delle prestazioni del sistema è stata basata sulla valutazione del consumo di energia totale e dell'uniformità di temperatura nel piano. Lo studio è stato in grado di suggerire quali layout dei riscaldatori sarebbero più efficienti rispetto a quello ottenuto con il design convenzionale: il consumo di energia può essere ridotto di una percentuale che va dal 26,6% al

39,6% e l'uniformità di temperatura può essere migliorata in una proporzione che va dal 20,3% al 39,6%. I risultati hanno anche evidenziato che le limitazioni sulla flessibilità di configurazione dei riscaldatori, dovute alle tecnologie impiegate attualmente, hanno un grande effetto sulla capacità del sistema di controllo termico di mantenere una regolazione fine della distribuzione di temperatura. Dopo aver esaminato i risultati della prima tornata di ottimizzazione, è stato selezionato un numero finito di layout ingegneristicamente fattibili, che sono stati successivamente utilizzati per il resto dello studio. Queste configurazioni semplificate introducono una degradazione accettabile dell'isotermia del pannello, ma allo stesso tempo consentono una fabbricazione semplice, con una riduzione di 17÷38% dell'area totale coperta da riscaldatori. Questo risultato dimostra chiaramente il vantaggio che può essere ottenuto con una sistematica ottimizzazione del progetto termico. Inoltre, tecniche di ottimizzazione multi-obiettivo sono state utilizzate anche in uno studio quantitativo a sostegno del beneficio ottenibile aggiornando la strategia di controllo termico da una semplice logica ON÷OFF ad una più complessa. In particolare, il lavoro è riuscito a quantificare i miglioramenti delle prestazioni che possono essere ottenuti con una legge di controllo proporzionale o proporzionale-integrale-derivativa. Inoltre, l'analisi ha mostrato i vantaggi di un controllore proporzionale-integrale-derivativo ottimizzato. Il risparmio energetico, per il caso in esame, può raggiungere il 34% rispetto ad una legge proporzionale, e raggiungere circa il 52% se confrontato con la strategia ON÷OFF. Questi benefici possono giustificare il prezzo da sostenere in termini di complessità di progettazione, e suggeriscono che, come regola generale, un notevole miglioramento del design può essere ottenuto a costo di appena poche ore di tempo di calcolo (meno di 24 ore su un processore Quad-Core, 3 GHz, 12 MB cache). Al termine del processo, l'ottimizzazione multiobiettivo è stata in grado di produrre una configurazione alternativa che ha dimezzato il consumo di energia e mantenuto una distribuzione di temperatura accettabile con una riduzione del 24% nell'estensione dell'hardware termico necessario (area degli elementi riscaldanti).

L'architettura della *smart skin* di ROV-E è stata ispirata proprio dai risultati di questi studi di ottimizzazione multidisciplinare. Prima di tutto, essi hanno reso chiari i vantaggi dell'uso di hardware termico distribuito e controllato in maniera fine, inoltre hanno dimostrato che la regolazione simultanea della disposizione geometrica, nonché della strategia di controllo e dei suoi parametri può portare ad un notevole risparmio energetico. In particolare, è chiaro che la granularità delle patch di riscaldatori previste dal re-engineering di ABB può portare ad un migliore controllo della distribuzione di temperatura nel piano. Tuttavia, le soluzioni identificate dagli algoritmi di ottimizzazione sono di difficile realizzazione se si pensa all'utilizzo di hardware termico standard commercialmente disponibile. Pertanto, la *smart skin* intelligente di ROV-E è mirata a sviluppare la tecnologia necessaria per una semplice e lineare implementazione di tale soluzione ottimale, accoppiando una capacità di carico termico distribuita con logiche di controllo adeguate. La fase di design di ROV-E non è ancora completa, ma è possibile riassumere alcuni degli aspetti chiave del progetto. Prima di tutto, come con i suoi precursori, la nuova *smart skin* ha l'obiettivo di ridurre i volumi occupati dalle scatole elettroniche convenzionali e dall'harness associato, distribuendo allo stesso tempo la funzione di riscaldamento in una zona più ampia, ed introducendo un concetto di design modulare con la possibilità di far fronte alle forme costruttive più disparate ed irregolari. Questi requisiti sono soddisfatti mediante l'utilizzo di un substrato polimerico che potrebbe essere polimmide o LCP. L'integrazione di uno strato conduttivo dedicato a resistori di potenza offre la capacità di focalizzare l'azione di riscaldamento solo dove questa è effettivamente necessaria o, in alternativa, di ottenere un controllo fine della distribuzione di temperatura sull'intero sistema. La scelta di protocolli di comunicazione a basso numero di fili consente un aumento del numero dei punti di monitoraggio senza un corrispondente aumento del numero di linee di segnale. Inoltre, essendo la stragrande maggioranza delle connessioni già cablata all'interno del modulo flessibile, si riducono la complessità di assemblaggio e gli errori umani durante l'AIT. Il piccolo numero di connessioni ancora necessarie per garantire la modularità e la capacità di interfaccia della *smart skin* sarà gestito mediante piattine a nastro accoppiate con terminazioni polarizzate. Un'altra caratteristica innovativa nel design di ROV E è la presenza pervasiva di funzionalità di calcolo, di rilevamento dati e di controllo nidificate all'interno del foglio costituente la scheda madre, grazie all'introduzione di chip ultra sottili, quindi in grado di ridurre le impronte e gli spessori associati ai circuiti integrati, e migliorare la flessibilità generale del prodotto finito.

Dopo il lavoro svolto con le campagne di test su ABB e sui dimostratori STEPS, il concetto di sistema multifunzionale basato su *smart skin* può essere dichiarato a TRL 5/6 dal punto di vista termico. Per raggiungere un TRL 5/6 complessivo, sono necessari ulteriori migliorie sotto i punti di vista della mitigazione EMI e della protezione dalle radiazioni. Questi aspetti devono essere trattati sia in termini di test sulle prestazioni degli attuali prototipi, sia in termini di miglioramenti incorporati nel progetto. Questi aspetti sono molto importanti per garantire l'affidabilità della *smart skin* in un'applicazione tipo satellite o rover. In particolare, lo studio EMI/EMC è di primaria importanza, mentre la mitigazione delle radiazioni potrebbe non essere così critica se l'applicazione prevista avesse una carenatura in grado di smorzare la dose di radiazione che raggiunge la *smart skin*. Ulteriori attività di verifica meccanica (ad esempio, test di vibrazione), potrebbero essere altrettanto utili. Tuttavia, questo aspetto non è così critico, poiché la *smart skin* è indipendente dalla struttura di supporto, e sono già disponibili significative esperienze e dati di test e di volo per quanto riguarda strutture convenzionali in alluminio o composito, che sono ben note ed ampiamente utilizzate nel settore spaziale. Anche il comportamento della saldatura dei componenti elettronici è abbastanza ben conosciuto. Ad ogni buon conto, parte di questo lavoro aggiuntivo necessario per migliorare il TRL della *smart skin* è già incluso in ROV-E.

Una nota particolare va fatta circa il possibile utilizzo della *smart skin* in una struttura gonfiabile o dispiegabile. Caratteristiche intrinseche come il profilo sottile, la flessibilità e la libertà nella disposizione geometrica rendono la *smart skin* un candidato ideale per l'introduzione di funzioni di health monitoring, controllo termico e distribuzione elettrica in una struttura non convenzionale. Per sviluppare ulteriormente questo potenziale, è necessario studiare una serie di problemi, vale a dire: i processi necessari per aggiungere la *smart skin* come ulteriore strato nel pacchetto utilizzato come parete per le strutture gonfiabili (ad esempio, formatura e cucitura. . .), le proprietà chimico-fisiche della *smart skin* attualmente sconosciute (ad esempio, effetto barriera, compatibilità con specifiche sostanze chimiche. . .), e non ultimo i problemi legati al montaggio ed alla riparazione dello strato una volta

che è stato incorporato.

Nessuno degli aspetti che devono ancora essere affrontati è uno show stopper. Molti di essi sono già stati trattati in altri settori industriali ed il punto principale è quindi quello di estendere la cultura dei circuiti flessibili all'industria aerospaziale. L'iniziale investimento in termini di acquisizione delle metodologie e del know-how tecnologico e di design[2] può essere ripagato ampiamente dai molteplici vantaggi di questa soluzione. I principali benefici includono: il risparmio notevole, maggiore del 50%, nella massa e nei volumi dei cablaggi[3], e delle schede elettroniche stampate, lo sfruttamento della terza dimensione nel layout dei circuiti, ottenendo così un prodotto adattabile a raggi di curvatura contenuti e forme strane, maggiore libertà nel posizionamento fisico dei componenti, uso di componentistica attiva e passiva distribuita per il rilevamento e l'elaborazione dei dati, costi ricorrenti molto più bassi ed hardware molto più ripetibile rispetto alla configurazione convenzionale con scatole elettroniche e cablaggi manuali, risparmio sui costi attraverso la forte riduzione o l'eliminazione del lavoro manuale.

Con riferimento alle applicazioni terrestri e civili, la *smart skin* potrebbe essere un'opzione possibile ogniqualvolta sia necessaria l'applicazione dell'health monitoring e del controllo termico per una struttura (strutture aeronautiche ed automobilistiche, cisterne o serbatoi industriali. . .). Le considerazioni sul TRL sono molto simili a quelle presentate per le applicazioni spazio, con l'eccezione delle questioni di attenuazione delle radiazioni. È un dato di fatto che l'elettronica flessibile viene già impiegata in prodotti civili, pertanto l'estensione dell'utilizzo della *smart skin* per applicazioni terrestri dovrebbe essere favorita.

D'altra parte, come alternativa al concetto di *smart skin*, vi è il concetto di sfruttare le prestazioni meccaniche dell'elettronica stessa per sostituire strutture convenzionali. In questo campo, lo studio svolto al JPL su micro rovers multifunzionali ha portato al design completo end-to-end di un piccolo dimostratore ed alla fabbricazione, all'assemblaggio ed alla verifica funzionale di due mock-up intermedi. Dopo un primo studio della letteratura riguardante piccoli sistemi robotici, si sono esplorate le tecnologie necessarie per mettere insieme il prodotto finale ed ha infine avuto luogo la fase di progettazione vera e propria. L'impianto elettrico ed elettronico del sistema comprende una unità centrale di controllo, un modulo di comunicazione wireless ed un convertitore DC/DC. Circuiteria aggiuntiva è stata progettata per l'azionamento di motori in lega a memoria di forma, la gestione di un modulo laser, l'acquisizione di sensori di pressione, ed il monitoraggio dello stato della batteria. Sotto un punto di vista meccanico, tutte le schede elettroniche che compongono il rover sono state modellate in 3D. La progettazione meccanica ha incluso anche lo studio di un gripper realizzato come meccanismo deformabile da utilizzare come end-effector di un braccio robotico a cinque gradi di libertà. Le attività di design hanno incluso anche lo sviluppo di tutto il software necessario

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[2] È innegabile che ci sono costi aggiuntivi non ricorrenti dovuti alla necessità di acquisire: i) competenze in materia di progettazione di PCB flessibili, che sono completamente differenti da quelle standard o rigido-flessibili, 2) metodologie di concurrent engineering con tutte le discipline di progetto coinvolte contemporaneamente, 3) specifici strumenti software per l'analisi e l'ottimizzazione multidisciplinari.

[3] I cavi realizzati secondo tecniche tradizionali hanno infatti un rapporto molto elevato, sia in peso che in volume, del materiale di rivestimento rispetto all'effettivo conduttore in rame [31].

per gestire le funzioni di comunicazione e movimento del rover. Fondamentalmente, il codice è stato suddiviso fra un modulo di basso livello residente sul robot, ed uno di alto livello residente sulla stazione di controllo (un computer portatile). Durante le fasi finali della attività di progettazione, le componenti strutturali di un primo prototipo sono state realizzate grazie ad un processo di fabbricazione in stereolitografia. Il prototipo è stato montato e collaudato, ed utilizzato come piattaforma di sviluppo per il miglioramento del software. Alla fine, un secondo mock-up è stato costruito, utilizzando una vera scheda elettronica rigido-flessibile, e provando così l'integrazione di tutti i componenti ed il funzionamento del sistema completo.

Vale la pena di spendere qualche parola nel definire lo sviluppo futuro del lavoro. Prima di tutto, le attività relative a ROV-E saranno continuate fino alla fine del 2013, con il completamento del progetto di dettaglio della *smart skin*, la fabbricazione di un dimostratore, e la sua campagna di test (prove termiche e meccaniche). Inoltre, dopo l'esito positivo del programma STEPS, Thales Alenia Space Italia ha deciso di applicare le tecnologie studiate per la *smart skin* al progetto specifico di un sistema distribuito di controllo termico che sarà sviluppato nel quadro del nuovo progetto STEPS2, nel biennio 2013/2014. Inoltre, nel prossimo anno fiscale, il micro rover studiato per il JPL sarà prodotto nella sua versione finale. Possibili modifiche ed aggiunte al progetto includono l'applicazione di elettronica stampata a getto d'inchiostro direttamente sulla struttura.

Questa tesi ha riguardato l'integrazione di molte funzioni in un unico prodotto, e tale proposito può essere realizzato soltanto studiando il problema da molti differenti punti di vista, in ogni fase del progetto. Quindi è facile capire come l'argomento sia sempre stato stimolante ed interessante in tutto il suo sviluppo. Oltre ai risultati ed alle considerazioni di tipo tecnico, il lavoro svolto per creare questa tesi ha incluso anche altri aspetti, che sono stati estremamente educativi. Si è trattato di impagabili lezioni sulla gestione dei programmi di ricerca finanziati internamente (dall'azienda) o pubblicamente (da qualche ente nazionale o sovranazionale). In particolare, è stato molto formativo partecipare alla redazione, presentazione e difesa di proposte di ricerca a livello nazionale ed europeo, grazie alle quali si sono raccolte la notevole esperienza delle attività preparatorie e la conoscenza del processo di revisione necessarie per presentare una offerta vincente.

Inoltre, il lavoro ha incluso un'esaltante esperienza pratica all'interno dei ranghi di due istituzioni di altissimo livello, all'avanguardia nel settore aerospaziale. Le mansioni svolte hanno coperto l'intero spettro di attività di ricerca, dalla progettazione al collaudo, dall'analisi alla fabbricazione. Di particolare interesse è stata anche l'esperienza nell'arte sottile di trattare con fornitori e clienti.

In conclusione, questo lavoro di ricerca è stato molto allettante e motivante, sia per la varietà di argomenti tecnici incontrati, sia per il generale bagaglio di soft skill acquisiti, che rappresentano un'altrettanto inestimabile risorsa professionale.

Preface

> *Research is what I'm doing when I don't know what I'm doing.*
>
> Wernher von Braun

This thesis was born in the context of a research activity conducted by Thales Alenia Space Italia, and called *Integrated Multifunctional Systems*.

The name is quite self-explanatory: the research is devoted to the study of Multifunctional Systems (MFSs). The work hereafter described addresses MFSs combining thermal, structural, electronic, and control functionalities.

The rationale behind this activity comes from a careful evaluation of mission drivers and constraints for space systems. In the last 30 years, studies [1] have shown that the largest contributors of total spacecraft dry mass are two technology areas: structure and packaged electronics. This information indicates a potentially fruitful area of technology development that would provide significant spacecraft dry mass reduction. Possible interesting areas to be addressed are bus architectures, novel electronic packaging and layout, electronic chassis that also function as structural members, minimization of harness. Moreover, there is increasing interest in the unnoticeable distribution of thermal control and monitoring hardware throughout the system. The challenge is to meet mission requirements taking into account an integrated design that addresses all areas of structural, electrical, component packages, and thermal elements.

In particular, for this thesis the aim was to identify different ways of combining electrical and thermal control functions with mechanical structures in order to create a multifunctional system able to save mass and volumes, and simplify integration. The scope of the work was to screen materials and technologies to be used for structural elements, thermal solutions, and integrated electronics, to conceive, design, manufacture, and test suitable prototypes, and to evaluate the application of multidisciplinary design and optimization techniques to this field.

The work has been conducted in close collaboration with Thales Alenia Space Italia S.p.A. (TAS-I), and with the Jet Propulsion Laboratory (JPL)/California Institute of Technology (Caltech). Over a three year timespan, four different demonstrators have been considered: three of them have been developed with TAS-I, and one with JPL.

In chronological order, the first prototype is the Advanced Bread Board (ABB), which is a thermostructural panel built in Carbon/Carbon and equipped with distributed electronics and sensors. The second prototype was implemented into three different demonstrators, SDA, SDB, and SDC (respectively, STEPS Demonstrator A, B, and C). They consist of an intelligent, modular, flat, and flexible motherboard which has been mounted on an aluminium sandwich panel, a curved aluminum plate, and a layer of Kevlar fabric. The third prototype is the ROV-E smart skin demonstrator, which is a development of the STEPS motherboard concept, and the fourth prototype is the JPL μRover, which consists of a small 4-wheeled robot made of thermostructural Printed Circuit Boards (PCBs).

The four prototypes represent subsequent steps toward the realization of a multifunctional system where electronics in flex and rigid-flex form is bounded with structure. The goal is to achieve a more distributed architecture equipped with enough intelligence to handle communication, thermal/environmental control, and actuation.

A synoptic is depicted in Figure 1.

ABB is the first example, where small flat and flex boards with limited intelligence are mounted on a structural substrate with high thermomechanical performances. After the results obtained from ABB, the design flow is ideally split in two branches.

The first research branch keeps on the development of flex electronics as a mean to integrate communication capabilities, health monitoring, signal and power harness on many different support materials: the STEPS demonstrators and the ROV-E smart skin concept are products coming from this approach. The STEPS demonstrators show increased dimensions, expanded capabilities, and higher level of on-board intelligence. The ROV-E smart skin brings these characteristics to their maximum extent: the design is focused on an extremely flexible board, able to monitor the surrounding structure and environment, able to actuate loads and to take care of signal and power distribution.

On the other hand, the second research branch explores the possibility of using the electronic boards themselves (in rigid-flex configuration) as structural elements: the JPL μRover is the product of this approach. The micro rover is supposed to show the viability of eliminating electronic boxes by transfering all the components on the primary structure, which is therefore made of Printed Circuit Boards based on particular thermostructural materials.

All the aforementioned points have been developed throughout three years of work, and it is important to recognize the contribution of several people who have been instrumental in reaching the final goal: colleagues in TAS-I and at the JPL who helped solving design issues and finding the proper direction for the activities, fellow PhD students who shared ideas, undergraduate students who took care of part of the analysis activities during their graduation projects, and suppliers from different companies who gave precious advice on the technical feasibility of the design and actually manufactured the different prototypes.

This thesis describes the work conducted for the development of integrated multifunctional systems from 2010 to 2012, and is divided in five main chapters, introduced by this preface. The preface itself presents the topic and scope of the work, and describes the research methodology used during activities. It also describes the structure of the thesis and acknowledges relevant contributions.

The first chapter is dedicated to the literature review. Its goal is to explore the

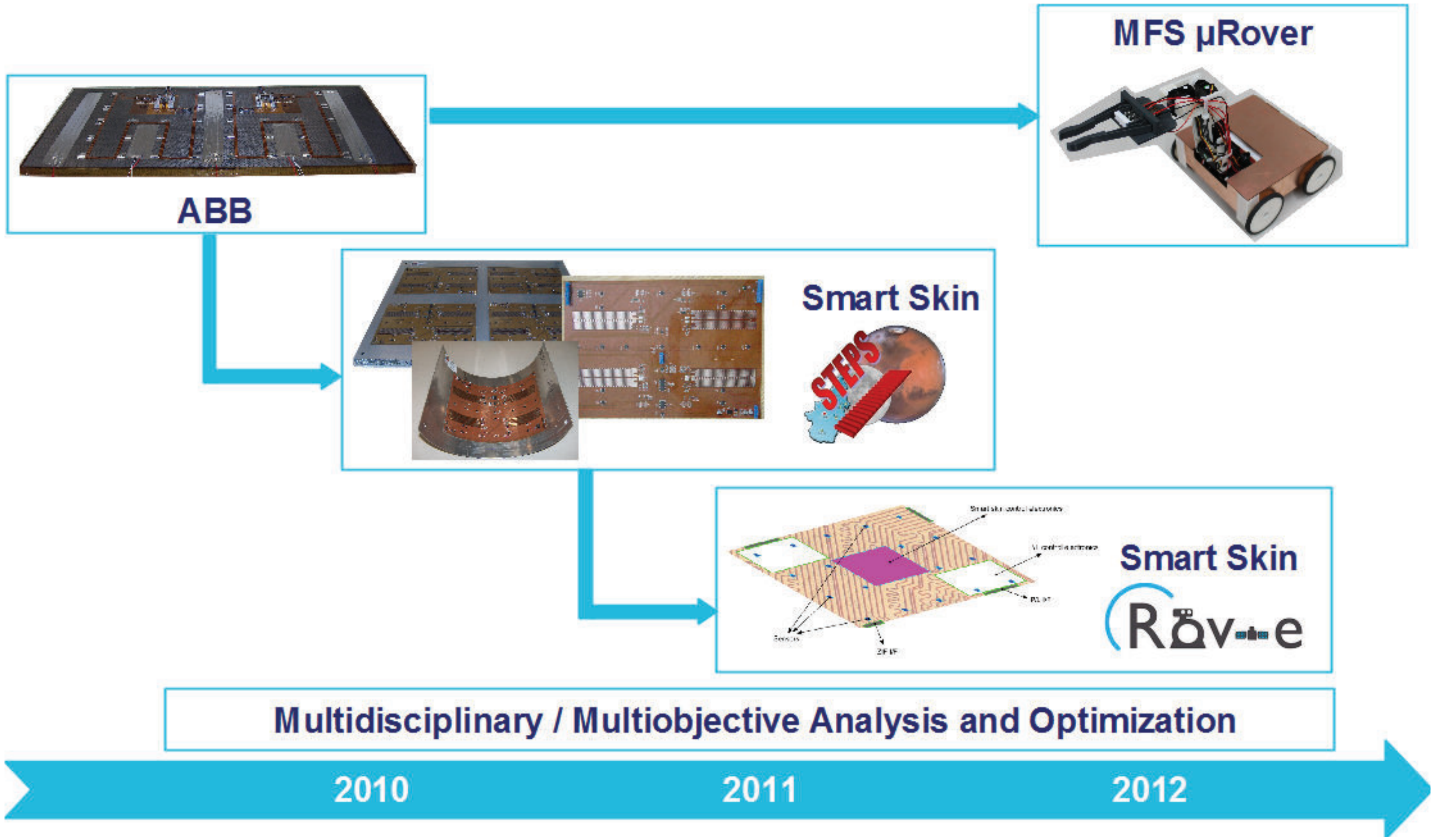

Figure 1: Synoptic of the four demonstrators.

state of the art, to gather and summarize information on activities that have been performed up to now in the field of Multifunctional Systems. These activities are the foundations on which the work described in this thesis has been conceived, and represent the benchmark for the evaluation of achieved results. Therefore, a section is also included which contains a critical analysis of the activities most strictly related to this thesis.

The second chapter presents how the research has been actually conducted, the activities regarding technology study and design, the factual implementation of concepts, the technical description of all different prototypes, and a first glance on results obtained.

The third chapter describes in more detail all the findings, including test results and interpretation of data.

The fourth chapter focuses on analysis and discussion of results and findings, with particular attention to their position in the context of the initial literature review and possible comparison with closest rivals.

The fifth chapter draws conclusions and explains where further work is needed and which activities are going on to bring the multifunctional systems approach from the laboratory to the space vehicle.

To broaden the discussion on given topics, or to give additional information on specific technologies, an appendix has been added.

Contents

Chapter 1

State of the Art

Literature Review

1.1 Introduction

This chapter is an introduction to multifunctional systems, and to projects and missions that have demonstrated or will use the multifunctional approach.

A first section will present a general description of the technology and its various aspects, mainly focusing on those pertaining to this thesis. The goal is to give an overall definition of the topic and go into further detail for those features addressed in the research activity.

A second section will introduce evidence of study and application of MFSs, summarizing all main examples worldwide available.

1.2 Generalities on multifunctional systems

One of the main concerns in aerospace engineering is the reduction of weights; together with this impelling guideline there are also other keywords such as cost effectiveness and high integration. The overall objective is to maximize the ratio of payload mass over total system mass.

In the last decades, all efforts toward this goal were focused on lightening of the primary structure, and therefore led to the massive replacement of metal structure with composites. Unfortunately, there is a saturation point in the benefit brought by this solution: maximum weight reduction is a modest percentage of the overall mass, due to the fact that structures represent just a portion (more or less one fifth) of the global system weight.

In order to achieve a stronger improvement, all factors responsible for the overall mass must be reduced concurrently.

Obviously, the well known motto “faster, better and cheaper” (but we may add “smaller and lighter” as well) does not mean to achieve mass and volume reduction at any cost. If so, we would fall back to the discouraging sequence of flops experienced by NASA in the 90s, when only 10 out of 16 missions achieved their objectives, giving a mere 62 percent success rate[1]. On the other hand we

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[1] According to [2], failures were encountered in Wide Field Infrared Explorer (WIRE), Mars

should interpret this guiding principle as an exhortation toward a more rational and optimal design.

As a response to these conflicting drivers, Multifunctional Structures (MFSs) represent a real breakthrough.

Complex system design has evolved over the past decade, moving away from discrete unifunctional subsystems with clearly defined boundaries, to produce systems, materials, and design methods that blend performance in new and innovative ways.

Many definitions of multifunctionality exists: according to distinguished experts [3], there are three sorts of multifunctionality, designated as Types I, II, or III. Type I multifunctionality is the addition of subsystems to provide additional performance enhancement to a primary or critical function. Most smart structures would be considered Type I multifunctional systems. Type II multifunctionality is the union or co-location of functions embedded within a system component. Type III multifunctionality is the integration of functions shared in a volume of material.

Then, it is also important to recognize that the described multifunctionality hierarchy occurs at different scales. Two or more functions can be integrated on several dimensional levels, with higher interconnectivity between phases and increasing engineering difficulty as the scale decreases. Type I MFSs describe phases in which one function is simply mounted, coated, or laminated to another, usually a structural component. Type II MFSs are composed of distinct phases in which one function is embedded in another, usually a structural component. Type III materials are truly integrated: phases are intermeshed, blurring the physical distinctions between them.

Apart from theoretical descriptions, basically, multifunctional structures are components that gather many functions within a single piece of hardware. This concept is amazingly interesting in the space field.

Given the fact that structures in spacecrafts are sized on the most demanding task (namely the harsh environment of launch), they result in being highly oversized during the rest of the mission; therefore it is quite natural to choose structural parts as the embryo of MFSs. Then other capabilities are added in order to accomplish further assignments with the same mass, preventing it from becoming just a dead redundancy.

It is worth remembering that, if on one side, the use of advanced technologies and the implementation of several functions bring remarkable advantages, pushing project race toward higher performances and wider control capabilities, on the other side integration of many subsystems needs higher development costs.

However, when constraints are too strict, multifunctionality can represent the only viable alternative. For example, multifunctional structures have been cited over recent years as an enabling technology for lightweight flight vehicles such as microspacecrafts and interceptors.

Climate Orbiter (MCO), Mars Polar Lander (MPL), the twin Deep Space 2 micro-probes (DS2), Lewis Satellite, and Clark Earth Observing Satellite. On the other hand, successful missions were Mars Global Surveyor (MGS), Mars Pathfinder, Deep Space 1 (DS1), Near Earth Asteroid Rendezvous (NEAR), Lunar Prospector, Stardust, Solar Anomalous and Magnetospheric Particle Explorer (SAMPLEX), Fast Auroral Snapshot Explorer (FAST), Submillimeter Wave Astronomy Satellite (SWAS), and Transition Region and Coronal Explorer (TRACE).

In the most classical approach, a MFS encompasses structural, thermal and electronic functions. All these tasks can be satisfied by means of different implementations:

- Mechanical integrity is achieved through the use of materials that can be more or less innovative, such as classical aluminium structures, traditional composites or C/C honeycombs. Even inflatable and deployable structures can become multifunctional systems.

- Thermal behavior can be handled both with the chemical and physical characteristics of the structure or with an integrated thermal control system (that can in turn be active or passive).

- Electronics can be coupled directly with the support structure, via flexible boards with no casing, reducing mass (both from the casing and from the PCBs) and eliminating a great quantity of external harness.

Obviously, other tasks can be demanded to a MFS, like in the research branch conducted at Southampton University [4] or in the LiBaCore project [5] conducted at the AFRL (Air Force Research Laboratory), where satellite structural and power systems are merged, embedding Li-ion batteries in structural panels. However, the key concept is always the same: exploiting a single device to fulfill many needs with a reduced mass.

In the remainder of this section, the most common aspects of MFSs are presented. The text will deal with:

- Structural performance
- Thermal control
- Embedded electronics
- Communication and distributed control

while an overview of other functions that can be performed by a MFS (like radiation shielding, embedment of propulsive power, electrical power generation and storage) can be found in literature [7].

1.2.1 Structural performance

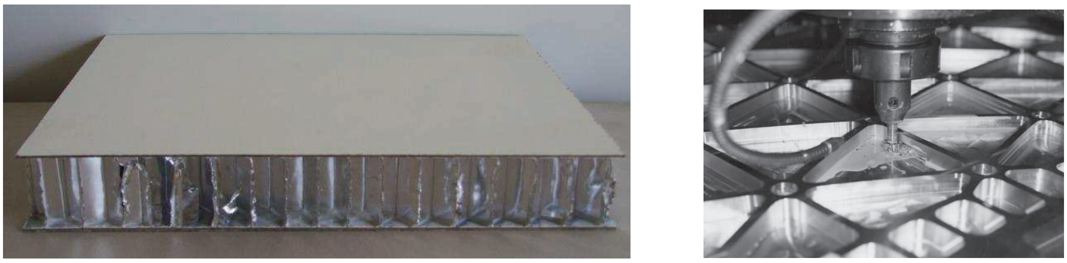

Figure 1.1: Examples of space structures: sandwich panels and integral panels.

The spacecraft structure is the essential base on which other functions are grafted. The challenging aspect in a multifunctional system is to ensure a full performance with the lighter possible solution.

When this goal is achieved, a number of possibilities arise:

- a conventional space mission can be carried out with a smaller, lighter and therefore cheaper satellite, paving the way to multi-satellite launches;
- new missions can be enabled thanks to the production of micro- and nano-satellites that, far from being smaller versions of conventional satellites, providing the same or comparable mission performance, offer additional new capabilities, which could become even more interesting when considering the deployment of several units in a cooperative mission.

The goal of lowering the structural mass is accomplished with the introduction of application-specific materials, chosen to reach the highest specific properties.

From a mechanical point of view, good candidate materials for MFS space applications should provide a number of qualities, such as:

- A thermal expansion coefficient (CTE) matching with the surrounding structure (for specific applications, like high-energy astronomy, CTE should also be as lower as possible).
- High stiffness and dimensional stability or, on the other hand, flexibility and foldability.
- Sufficient strength to survive a launch.
- Low outgassing to avoid contamination (mainly with regard to the payload), or low permeability to ensure a leakproof enclosure.
- Manufacturability, mainly in relation to the realization of complicated shapes or very tight dimensional tolerances.
- A particular radiation length, in order to avoid instrument interference.

Conventional aluminum structures are still widely used, while new generation solutions include:

- High thermal conductivity composites, in particular carbon-carbon (C/C) products.
- Metallic foams.
- Functionally graded materials.
- Fabrics to be applied in deployable and inflatable structures.

This section will focus on the two items which are of most interest in the framework of this thesis, namely carbon-carbon materials and fabrics, while additional detail and discussion can be found in previous work [7].

A good example of the advantages brought in the space field by high thermal conductivity composites, and in particular carbon-carbon (C/C) composites, is the research [6] conducted by Hytec Inc. in year 2000, as part of R&D efforts funded by DOE and NASA, dealing with the innovative structural and cooling arrangement for the silicon-based high energy gamma-ray ($0.01 - 100\ GeV$) tracking detector that is part of the GLAST instrument concept.

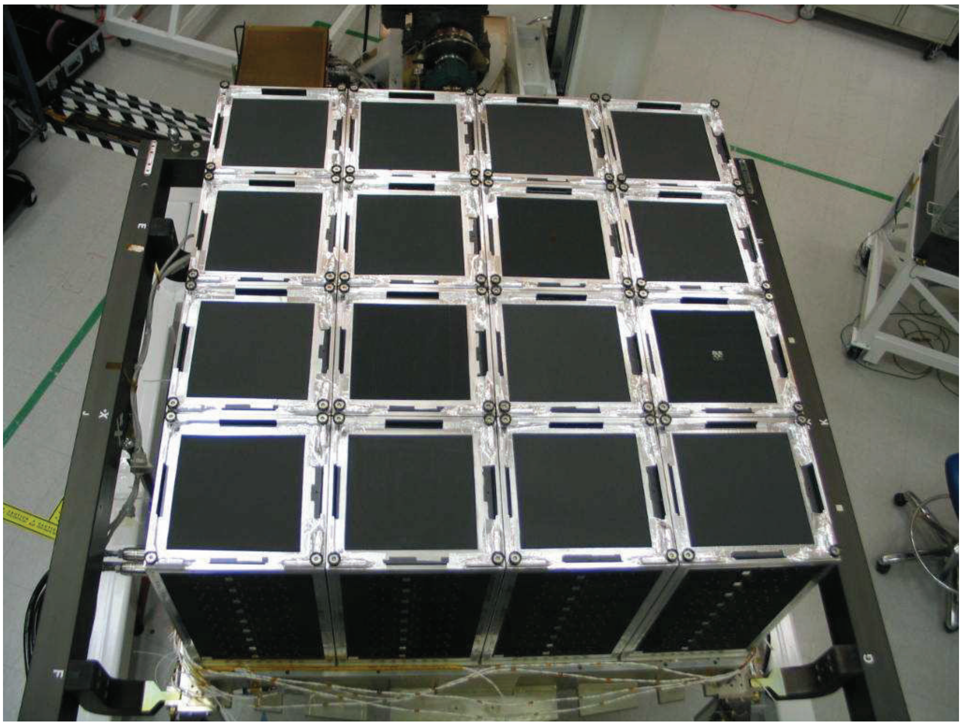

Figure 1.2: The GLAST tracking detector has nearly 900000 detector channels, each connected to its own amplifier. Packed into 16 compact modules are nearly 80 square meters of solid-state silicon detectors and 576 electronics boards, all supported on a carbon-composite structure.

High stiffness, tailored CTE, specific radiation length, and low outgassing were intended objectives in the final structure and a trade off was carried out among beryllium, resin matrix graphite fiber reinforced composites, and carbon-carbon composites.

Beryllium, with the longest radiation length and a high stiffness-to-density ratio, has always been a classical favorite choice in high-energy particle detectors. However, the relevant CTE ($11.3 \cdot 10^{-6}$/°C) together with the very high elastic modulus of beryllium would lead to large, unacceptable thermal strains when coupled with materials showing a much more limited CTE, as in the case of HE silicon detectors ($2.3 \cdot 10^{-6}$/°C). Under a similar mismatch condition, maintaining the precise alignment and relative positioning of the instruments for calibration purposes would not be possible[2]. In addition to the thermal expansion problem,

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[2] From the same Hytec research we can have an indication of this phenomenon: the height of a beryllium tracker tower with 17 trays would expand and contract by more than 220 microns under a ±20°C temperature variation, while alignment tolerances for the GLAST trays are about 50 microns.

beryllium is an hazardous material, requiring extreme precautions in machining, which makes it an expensive option.

Resin matrix graphite fiber reinforced composites also have long radiation length and high modulus. However, their worst defect is not structural but thermal: conductivity is relatively poor, especially in directions transverse to the fibers. The transverse conductivity of graphite fiber/resin composites is only about 2 $W/m/K$, compared to 146 $W/m/K$ for beryllium and more than 30 $W/m/K$ for carbon-carbon composites. Moreover, in the realization of small, relatively complex shapes, it may not be possible to embed fibers in the general orientation of the main thermal fluxes, leading to unacceptable temperature gradients. Resin based composites also have very high CTE in directions transverse to the fibers. In addition, machining of resin-based composites is difficult, particularly when extremely tight dimensional tolerances are required. Finally, an amount of raw exposed machined carbon composites can be found all around the finished piece, with exposed graphite fibers and carbon matrix that rise a concern of electrically conductive carbon particles being released from these surfaces during assembly and launch, and re-depositing on critical electronic components or wire bonds.

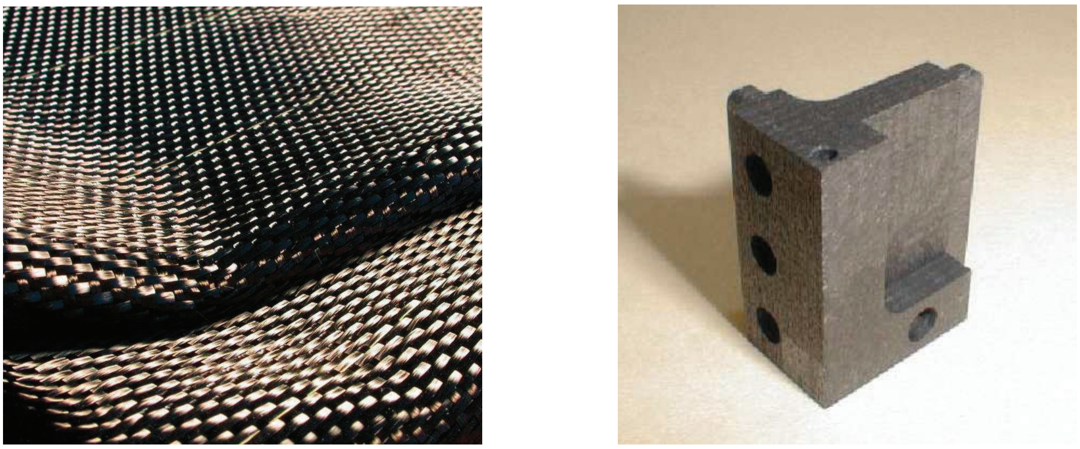

Figure 1.3: Carbon carbon in various sorts: fabric and milled piece.

Carbon-carbon (C/C) composites provide the best combination of high thermal conductivity, high stiffness to density ratio, good CTE (even matching the one of silicon detectors) and no outgassing. The transverse thermal conductivity of C/C is 15 to 40 times better than that of polymeric matrix composites. The properties of C/C, like that of a polymeric matrix composite, are also tailorable. However, its thermal and mechanical properties are more isotropic than those of resin based composites, making it more forgiving in applications with complicated geometry and/or a large amount of machining. Its radiation length (23 cm) is second only to Beryllium (35 cm), and by a small margin to that of polymeric matrix composites (25 cm). It is also very easily machined (in contrast to polymeric matrix composites), and presents no health hazards in this respect. The substantial porosity of C/C materials may cause difficulties with trapped gases that could be slowly released in orbit and cause contamination problems: an appropriate resin impregnation technique could eliminate those concerns.

In the aerospace field there is a wide interest in inflatable and deployable

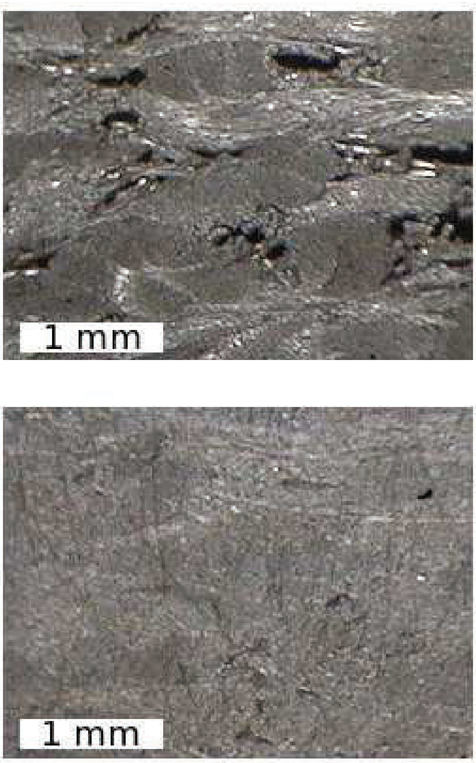

Figure 1.4: Resin impregnation of C/C: once impregnated the pores and cracks are almost entirely filled with resin, which considerably improves toughness and strength; the resin impregnation also reduces the tendency for C/C materials to release carbon dust.

structures, because they can be packaged into small volumes for flight, and at the same time deploy wide surfaces or large volumes when needed. Solar arrays and concentrators, antennas and reflectors, space habitats, rigidizable booms and beams, and various devices used during the Entry Descent and Landing phase, like Inflatable Aerodynamic Decelerators (IADs), parachutes, landing airbags (see [14] and [14] for a detailed discussion).

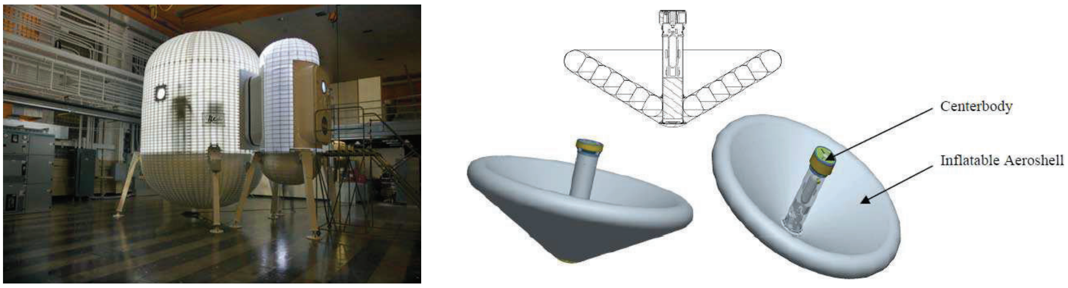

Figure 1.5: Two examples of aerospace inflatable structures: a space habitat concept by NASA [12] on the left, and the IRVE aeroshell system [10] on the right.

For inflatable and deployable structures, fabrics have been considered as a viable solution since the beginning of the history of tethered balloons and aerostatic vehicles. Candidate materials ranged from cotton, to neoprene, to nylon, and to Dacron-Mylar-Tedlar laminate, always trying to achieve greater strength-to-weight ratios, low permeability, and high resistance and adaptability to the environment.

A woven fabric consists of two mutually orthogonal families of yarns which can be interlaced in several different styles. Most of the terminology used for engineering woven materials is borrowed from the textile field. The *warp* yarns are the ones that are continuous for the entire length of the cloth, because during manufacturing they run in the direction of the roll. The *fill* yarns are the short yarns which run crosswise to the main cloth direction (along the short dimension of the roll). The *bias* is the direction at 45 degrees to warp and fill yarns, therefore woven fabric has two biases, at right angles to each other, and fabrics which are not woven, such as felt, do not have a bias. Coated woven fabrics exhibit unique behaviors under load: the stiffness of a woven fabric material is influenced by its biaxial load state. Moreover, when loaded in the bias direction, woven fabrics have a resultant stiffness that is quite low as compared with the warp and fill directional stiffness.

As soon as Kevlar®became available, a huge interest arose both from private industry and from Governments [8]. This new organic, high strength, high modulus aramid fiber represented an ideal solution in the field of structural use of filamentary materials, because it had strength-to-weight ratios 2 to 3.5 times that of Dacron, and ten times that of steel, well in excess of all other materials fabricated using conventional textile technology. Studies ([9], [10], [11], [12], [13], [16], [17] among others) are still going on, to determine how to manufacture practical inflatable materials and systems using Kevlar, and to measure their properties (fiber rigidity, strength, and weight characteristics under uniaxial and biaxial loading, abrasion resistance, crease effects, peel strength, blocking tendency, helium permeability, and joinery techniques to name just a few).

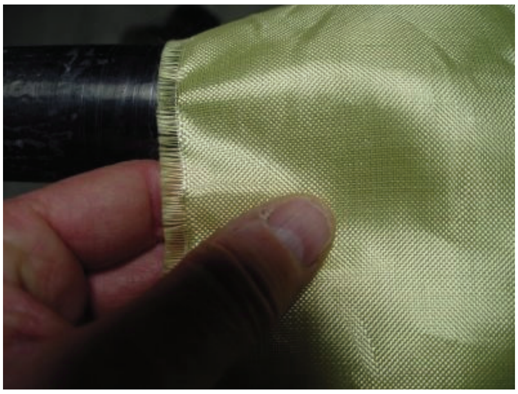

Figure 1.6: Lightweight (2.5 ounce/sq yd) bi-directional Kevlar cloth.

1.2.2 Thermal control

When it comes to the management of the thermal environment, several possibilities are offered by MFSs. In this field, both active and passive thermal control philosophies are used, leading to many different solutions.

In addition, the TCS (Thermal Control Subsystem) can be devoted to the spacecraft thermal management, to the electronics thermal management, or both, depending on several factors such as the S/C dimensions and the typology of electronical hardware involved.

The thermal control of the whole spacecraft is an aspect of particular interest because of the current trend toward an increasing power density installed on satellites: multifunctional structures can help facing the demanding task of dissipating heat in such an harsh context (nowadays satellites must withstand higher operative temperatures, a great number of hot spots, adverse thermal gradients. . .).

If the level of integration required by the project is not so high, a solution can be the embedding into the structure of thermal control only. In this case, the additional function required for the structural panels is to radiate the heat generated by different subsystems (not merely the electronics), so as to ensure thermal protection for all components.

The simple integration of thermo-structural tasks can lead to a better handling of high power densities, accounting for a lower mass and a simpler layout, pushing toward a stronger standardization.

Such a basic technology has been demonstrated onboard the MightySat II.1 spacecraft, launched in July 2000[3]. This design proved to operate as predicted. The structural panel performed thermal management: the thermal energy dissipated by the different subsystems was conducted and radiated to maintain the components in their operational range of temperature.

Generally speaking, the key concept is that, if properly chosen, the material of which the structure is made can offer on its own a good support, thanks to its thermal properties. For example, the structure can be made of high conductivity composites (advanced C/C panels, sandwich panels with carbon cyanate-esther skins and aluminium core, panels with foam core. . .), while thermal doublers can be attached to the structure to enhance its performance and allow it to replace conventional radiators.

Besides the exploitation of a suitable material, in order to reach higher thermal performances embedded control apparatus can be added: mini and micro heat pipes, capillary pumped loops, thermal switches, resistance heaters, conductive couplings at mounting interfaces. . . It is also possible to handle coatings for the exposed surfaces with desired optical properties. Temperatures of exposed surfaces of the spacecraft and the heat rejected by radiator surfaces can be controlled using variable emissivity materials[4]. Active thermal control with variable emissivity coatings also

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[3] The MigthySat program was conducted jointly by the AFRL and the Department of Defense (DoD).

[4] Variable emissivity coatings offer an alternative that is uniquely suitable for micro and nano spacecraft applications. This permits adaptive or “smart” thermal control of spacecraft by varying effective emissivity of surfaces in response to either a passive actuator (e.g., a bi-metallic device) or through active control from a small bias voltage signal. In essence the variable emittance surface would be an “electronic louver”. It appears possible to develop such “electronic louvers” through at least three different types of technologies:

- Micro Electro-Mechanical Systems (MEMS) technology; micromachined louvers or shutter arrays are used to demonstrate thermal control by varying the effective thermal emissivity of a radiator surface. At present, a number of louver and shutter prototypes have been designed and tested. The most promising design is microshutter arrays, actuated by small electrostatic comb drive motors.

- Electrochromic technology; an ideal means for thermal control of satellites is to be able to change the absorbance or emittance properties of a radiator depending on changing thermal conditions. The hot (around 7 μm), in-sun condition requires low solar absorptivity eliminates the need for bulky and heavy mechanical louvers for emissivity control, thus saving weight and volume of spacecraft systems.

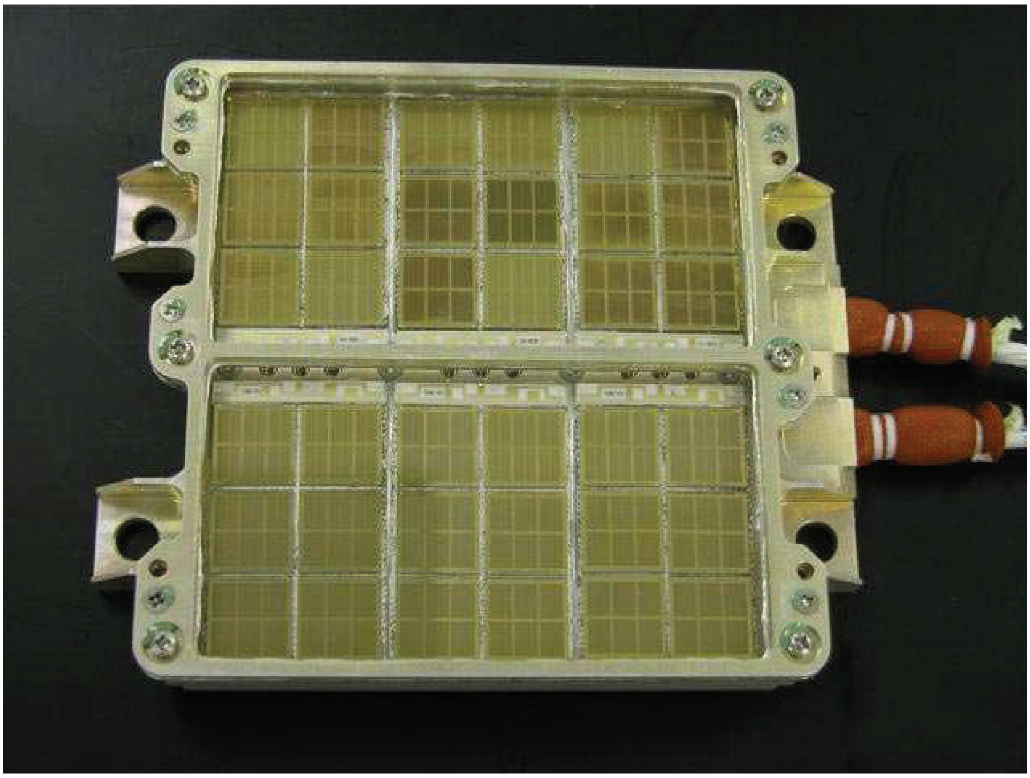

Figure 1.7: Close-up view of the 4-inch square microscopic radiator placed on the skin of one of NASA's Space Technology 5 (ST5) micro-satellites. The temperature control device, formally known as the Variable Emittance (Vari-E) Coatings for Thermal Control, is based on MicroElectroMechanical Systems (MEMS) technology employing shutters so small that several abreast are smaller than the width of a single human hair. The device was developed by the Johns Hopkins University Applied Physics Laboratory, in conjunction with NASA Goddard Space Flight Center.

It is worth mentioning that particular fields for the exploitation of MFSs for thermal control are the following:

- small spacecrafts[5], whose thermal control pose special challenges due to restrictions on volume, mass, and power available for thermal hardware: often the current thermal control technologies are not adequate to meet the science

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but high emissivity surfaces. During cold (around 12 μm), eclipse conditions, the satellite surface must have low emissivity. The goal is to keep the satellite at room temperature. Because of their light weight (5 g/m^2), low power requirement (1 mW), and wide range of reflectance modulation (0.8 change), ECDs (ElectroChromic Devices) are an excellent thermal management technology for satellites and spacecraft.

- Electrophoretic technology; devices have been proposed which resemble a liquid crystal display, with suspended flat particles in a fluid. When an electric field is applied, the highly reflecting particles align themselves to form a flat reflective surface.

[5] We define here small spacecrafts those under 100 kg and 100 W, expected to be used especially in space science missions.

objectives of these missions, therefore advanced thermal technologies and architectures are needed to meet the requirements of these future spacecrafts;

- deployable radiators, where MFSs could have a good application, using high-conductivity anisotropic materials;
- exploration rovers, that need a TCS characterized by light weight and flexibility, that allow for easy mechanical integration.

Even if the spacecraft thermal control mentioned in the previous subsection is important, the main motivation to the embedding of thermal functions into the spacecraft's structure comes from the integration of electronic components onto the structure itself.

Printed circuit boards can be very dense, thanks to improved fabrication processes that allow smaller vias, trace line width and spaces, and pad size. This can also be combined with designs that have multiple internal conductive planes (PCBs easily reach 20 to 25 layers). This high power density affects printed circuit board designs for space electronic applications. To ensure proper temperature ranges, the heat must be conducted away from the component who generates it (e.g. microprocessor or power device). The thermal path is through the printed circuit board to the board frame or chassis and to a suitable radiator. To improve the efficiency of that path, thick copper layers and thermal vias are used: the result is an undesirable increase in mass and thickness.

Electronic components are operational in strict temperature ranges and so must be kept between their limits, though they reject heat. Flexible circuitry is able to operate at temperatures up to 80 deg C, so that it is less demanding in terms of thermal control than conventional circuitry. However, in this case, the aim of the thermal management function of the panel is then to specifically control the electronics temperature to maintain them in their operational range.

To achieve thermal control for electronics, in a conventional spacecraft, radiators are mounted around the electronics, forming what is called a black box. In the MFS concept, in order to achieve thermal management, the same solutions discussed in the previous subsection are available. The projects conducted so far include the use of either high conductivity composites, combined with straps and doublers, or miniature heat pipes embedded into the structure. In particular, the use of embedded HP is quite well known ad applied.

Studies have been performed in order to fit the thermal properties of high conductivity composites, combined with straps and doublers, for the necessities of electronics. For example a design option to achieve efficient MCM (Multi Chip Module) cooling, while minimizing mass and volume, are structural panels made of high conductivity composite materials in which, in order to enhance the thermal efficiency of the panel, a high conductance carbon-carbon thermal doubler must be placed under the MCM, to reduce the thermal gradient experienced by the MCM ceramic base. A high conductivity filler must be placed in the honeycomb under the MCM to enhance heat rejection.

In other cases, the heat rejected by heat sources (power supplies, sun side, electronics) would be transported by an active coolant fluid to devices which need to be heated, or dump to a radiator panel. The micro tubes for the fluid routing would be directly embedded into the structure[6].

But there is another way to improve the thermal control of electronics, eliminating hot spots, lowering the average temperature, and improving heat rejection. This way is to improve the thermal conductivity of the board itself. There are materials that offer a more efficient thermal transfer onboard the PCB, therefore helping in the thermal control effort and even improving the behavior of the board itself as a radiator.

1.2.3 Distributed control and electronics

Spacecraft are filled in electronics packages performing the command and data handling, and power distribution functions. The main functions of the spacecraft onboard command and control hardware are: the acquisition of data from sensors, the commanding of actuators, the transfer of packets of data between onboard instruments and control computers, the distribution of time information.

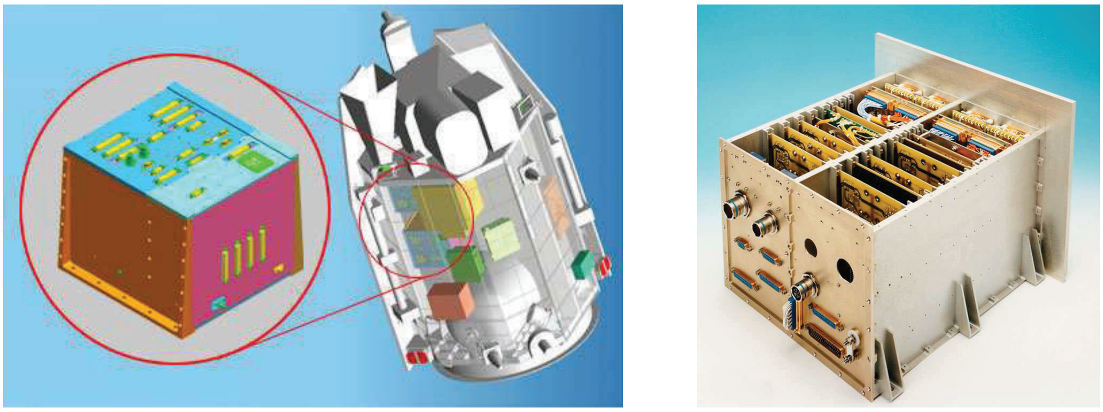

Figure 1.8: Typical satellite electronics is bulky and fills relevant volume percentages.

As already mentioned in the previous subsection, in a traditional approach, these components consist in bulky black boxes, thermally controlled by radiators, linked together with other subsystems by connectors and cables. The actual mass and volume of the electronics components are very small fraction of their packaging.

On the other hand, from a MFS point of view, there is the concept to mount the spacecraft's electronics onto its structural panels and to design the structure itself so that it achieves thermal control and shielding for these electronic components.

Fortunately, progresses made in the microelectronics field during the past 30 years has led to design small chips and high density flexible circuitry, which allows mounting electronic components directly onto the load bearing panels. Replacing the conventional electronics packages by such circuitry would yield significant mass and volume savings, both at the subsystem and at the system level.

One interesting and widely tested advance in microelectronics is the Multichip Module (MCM). The MCM technology replaces the conventional circuit board by

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[6] Idea from a study performed at McDonell Douglas Corporation that envisioned embedding electrical conduit, for power routing, miniature heat pipes, for thermal management, and optical fibers, for data routing, into the structural panels of the spacecraft.

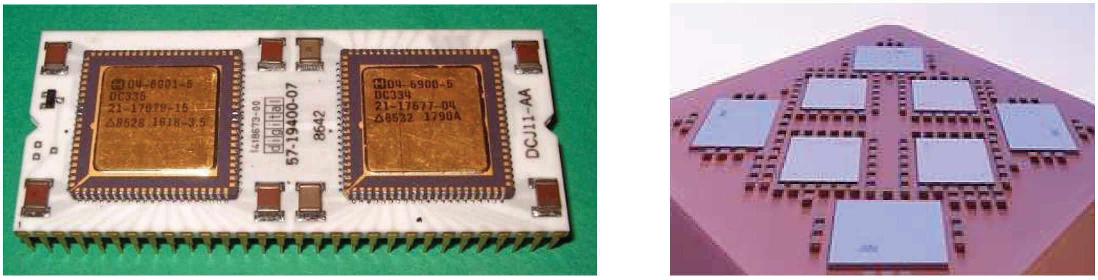

Figure 1.9: Examples of commercial and industrial Multi Chip Modules.

Table 1.1: Differences between standard electronic equipments and the new kind of apparatus described in this section.

Standard electronics	**New-generation electronics**
Bulky and heavy boxes	Mass and volume saving up to 10 times
Cumbersome and heavy connections	Almost zero cable connections
High costs	Half the cost
Complex mission-dedicated design	Possible standardization and flexibility

mounting chip dies onto a ceramic substrate. The motherboard is then replaced by multilayer copper/polyimide (Cu/PI) circuit patches which integrate sockets where MCM are mounted. The chips and interconnections of the circuit are made of traces of copper sputtered on a polymer sheet such as Kapton.

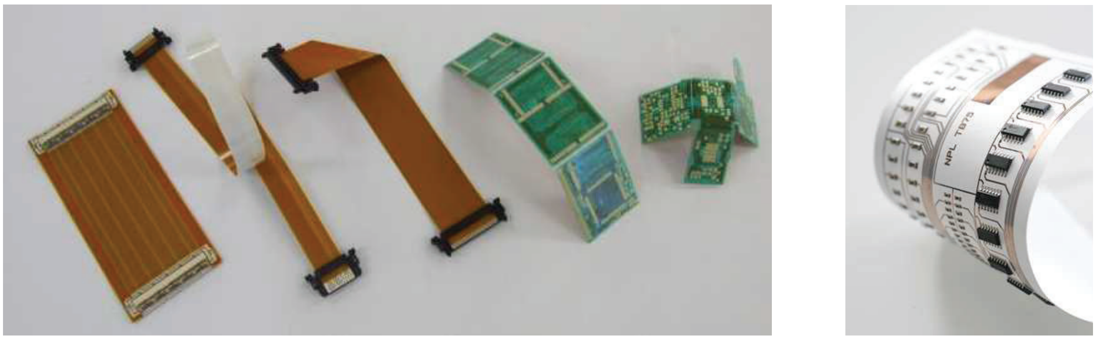

Figure 1.10: Flexible circuitry and flexible electronics.

Even connectors and cables are replaced by Cu/PI flexible jumpers, which connect circuit patches together[7].

Besides these, High Density Interconnects (HDI) are used to transmit signal from the MCMs to the external world without the help of any connector. These circuits are mounted onto structural panels with the help of space qualified adhesives.

The architecture of safety critical systems, such as flight control systems, is usually fully centralized. However, a new trend for modern spacecrafts is moving

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[7] These flexible jumpers are able to connect circuitry even from one panel to another.

towards distributed processing. In this new approach, specialized microcontrollers are used to control intelligent actuators over a digital communication bus.

Summing up, satellite electronics is evolving toward minimization of volumes: integrated electronics uses printed circuits that reduce the need for connectors and when these are necessary they are implemented as printed tapes that allow a better standardization with an high mass-to-volume ratio. Controllers and sensors are made of chips mounted on motherboards or directly on bare surfaces and connected by circuits embedded in structures.

This kind of electronics is also expected to lower production and installation costs, while allowing re-use of equipments for several missions. See Table 1.1 for a comparison.

1.3 Missions and Projects

For all the reasons mentioned in the previous section, in the aerospace community there is a wide range of research programs focused on different flavors of multifunctional systems. In this field, a lot of work was done since the 90s. The concept started from industrial and governmental efforts toward more cost- and mass-effective aerospace products and spread into a rich and diversified academic research branch.

At the present day, MFS technology readiness level is more advanced in the UAV field than in the space field: this is mainly due to the strong military interests in perfecting Unmanned Aerial Vehicles. Unfortunately, the technological transfer between aeronautic and space products is not so straightforward as it could seem. In particular, from a mechanical and thermal point of view, a space-born structure is due to withstand a much harsher environment and therefore all its parts have to show compliance with requirements that are more demanding than those of air-borne systems.

Nonetheless, at the present time a remarkable quantity of projects about application of MFSs to both space and aerial vehicles can be found. The remainder of this chapter will present a number of activities and their results, where available. It is worth noting that only wide, system-oriented activities are collected here, while specific technology-oriented activities have been dropped. Otherwise, given the huge variety of research work done worldwide to improve single MFS aspects[8], a much longer list would have been necessary.

Outside Europe, MFS research activities were carried on mainly in the United States. Here, multifunctional systems embedding electronics, thermal control and radiation shielding, have been the subject of a number of studies at NASA Centers, Air Force Research Laboratory/Philips Laboratory (AFRL/PL), Ballistic Missile Defense Office (BMDO), Defense Advanced Research Project Agency (DARPA), and Lockheed Martin Astronautics (LMA). All the technological challenges have been addressed: challenges in microelectronics technologies, in composite structures, in thermal control, and radiation shielding. Demonstration panels and flight prototypes

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[8] Laboratories all over the world are focusing on single technologies such as functionally graded materials or panel-embedded batteries (refer to the first chapter and to literature [7] for additional information).

have been manufactured and tested, so that the technology is now usable in space. Furthermore, demonstration panels have already flown onboard pioneering spacecrafts.

In Europe, wide programmes on the development of multifunctional systems are less numerous with respect to the USA. Nonetheless, the active projects show a bright interest of industry and space agencies an this topic. Furthermore, significant activities are carried on in co-operation among several different countries.

1.3.1 STEX (Space Technology Experiment)

STEX was a low-cost and low-mass technology demonstration mission sponsored by the US NRO (National Reconnaissance Office), an intelligence-gathering agency of DoD, and operated by AS&T (Advanced Systems and Technology) of NRO.

The overall objective was to demonstrate high-performance spacecraft technologies (29 in all) in space. The experiments conducted provided potential improvements in spacecraft technology for both military and civil satellites.

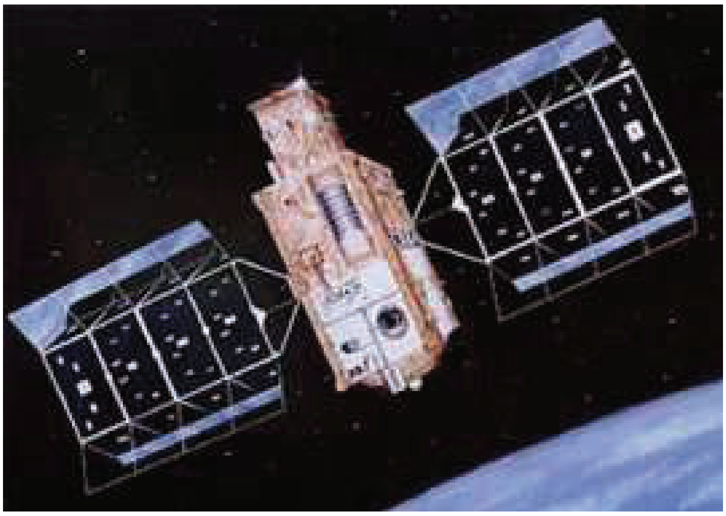

Figure 1.11: STEX satellite successfully tested over two dozen advanced technology subsystems. Among STEX's main equipment were Hall Effect electric thrusters derived from Russian technology, experimental solar arrays and batteries, and the Advanced Tether Experiment (ATeX), which was a follow-on to the earlier TiPS (Tether Physics and Survivability) satellite.

The STEX spacecraft was built by Lockheed Martin Astronautics Corp. of Denver as prime contractor. The spacecraft showed a body shell using low-mass composite structures and two tracking solar panels. The STEX bus was multifunctional because it integrated spacecraft electronics, structural, and thermal control functions into a single structure. In particular, the MFS concept involved interesting aspects about electronics: the embedding of passive electronic components within the actual volume of composite materials and new approaches to mount active electronic components directly to mechanical surfaces, using surface areas for mounting sensors and transducers. This new installation technology considerably reduced spacecraft mass and volume.

The first MFS demonstration based on STEX concept was flown on DS1 (Deep Space 1, launch Oct. 24, 1998) of NASA, the second on EO-1 (Earth Observing, launch Nov. 21, 2000) of NASA, and the 3rd test was on the STRV-1d (Space Technology Research Vehicle-1d, launch Nov. 16, 2000).

1.3.2 New Millennium Program (NMP) Deep Space 1 (DS1)

NASA's New Millennium Program was created to accelerate the insertion of advanced space related technologies into future space missions using deep-space and earth-orbiting technology validation spacecraft. The technology validation efforts of the NMP are focused around six technological areas:

a) Spacecraft autonomy.

b) Telecommunications.

c) Multifunctional and modular structures.

d) In-situ instrument and micro electromechanical systems.

e) Instrument technologies and architecture.

f) Microelectronics systems.

For each technology area, teams (integrated product development teams or IPDTs) consisting of representatives from NASA and other government laboratories, industry and academia have been formed to develop and provide the validation articles to be flown in the different space missions.

As can be seen, Multifunctional Structures have been selected as one of the most critical applications for advanced spacecrafts.

In an AFRL/PL, BMDO and DARPA sponsored program, Lockheed Martin Astronautics has successfully developed and demonstrated the design, integration, assembly, and functional performance of the MFS technology and its elements.

Given the novel nature of the MFS design, extensive development testing was performed prior to any DS1 design effort. This testing included vibe, thermal, x-ray, and electrical performance of a variety of test panels with different configurations of hardware. The technology was fairly well documented leading into the DS1 experiment design. DS1 components were tested both individually and as a system.

Deep Space 1 was a pure Technology Validation Mission. It was launched from Cape Canaveral on October 24, 1998.

During a highly successful primary mission, it tested 12 advanced, high-risk technologies in space, included, as already mentioned, MFS (electronics integrated in a structural panel, provided to NASA by the Air Force and built by Lockheed Martin).

During its fully successful hyperextended mission, DS1 conducted further technology tests.

The spacecraft was retired on December 18, 2001.

The demonstration panel consisted of a high-low power distribution module, a thermal simulator MCM, and a radiation hardened composite structure.

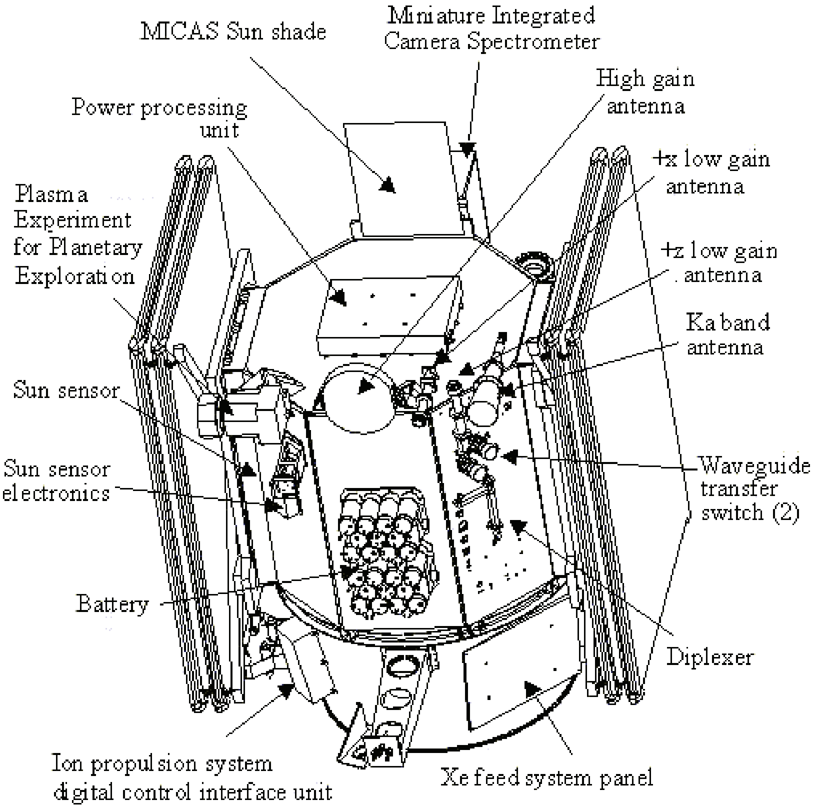

Figure 1.12: View of DS1 satellite with folded solar panels.

During the DS1 mission, the MFS experiment was powered up once every two weeks and two experiment cycles were carried out to ensure that a full set of data was collected. The experiment sequence provided a data set containing health and status information, electrical conductivity test data and (following a warming time period of the panel) thermal-gradient measurements.

In the electrical circuit performance area, conductivity measurements were taken during each experiment cycle to independently verify the nominal-trace conductivity, the performance of the anisotropic bonds in a jumper configured for multiple serpentined connections, and a set of daisychained connections to the thermal-simulator MCM through a socketed-lead system. A set of temperature measurements were collected to evaluate the thermal performance of the panel underneath the thermal-simulator MCM by using an array of sensors mounted on a flex-circuit tether. Finally, routine health- and status-data were collected to verify proper controller operation during the data collection.

The experiment was an incredible success based on the data returned. All health and status data was correct and within normal limits. The electrical-conductivity data never varied by more than one Least Significant Bit from the preflight data set. The thermal-gradient data was appropriate for the position of the sensors with respect to the heat source in the MCM.

This experiment demonstrated:

- feasibility of integrating flex interconnect, circuit patches, flex jumpers, thermal doublers, radiation-hard composite spot shield and structural substrate;
- feasibility of replacing conventional electronics boxes by embedded flexible circuitry onto the structure, protected by thermal doublers.

According to LMA conclusions, MFS technology is eminently suited to be used in many missions for the following reasons:

- it leads to significant mass (>50%) and volume (>2X) savings over traditional packaging systems;
- it takes full advantage of MCM devices without adding packaging mass due to printed wiring board (PWB) mounting;
- it eliminates the need for traditional form factors in spacecraft design;
- it is an enabling technology for wiring density in microspacecraft (thanks to flex circuitry);
- it is a key technology to support mass production of spacecrafts for constellations;
- it paves the way to inflatable structures (the techniques can be easily transferred).

Summing up, the NMP-DS1-MFS experiment has been very successful in demonstrating the majority of key features and showing that there are no major roadblocks. Even a minor rework was performed smoothly with the panel in place on the spacecraft bus. The MFS experiment was integrated quite easily on the spacecraft-bus panel and was the first technology experiment to be delivered to DS1.

1.3.3 New Millennium Program (NMP) Deep Space 2 (DS2)

Deep Space 2 (DS2) transported two microprobes, each weighing 2.5 *kg*, to analyze soil, search for ice and demonstrate technologies that will enable network science for future missions.

The probes, which piggybacked aboard the Mars Polar Lander, were to slam into Martian soil December 3, 1999.

The microprobes were designed to withstand both very low temperatures and high decelerations. Each highly integrated package included an advanced microcontroller, a telecommunications microsubsystem, power microelectronics, an ultra low-temperature lithium battery and flexible interconnects for system cabling.

Figure 1.13: The disassembled parts of the Deep Space 2 probe, the forebody and the aftbody, as compared in size to a quarter. The two parts are linked by an umbilical (flexible interconnect).

The microprobes were divided into a forebody and aftbody. The forebody, which was supposed to lodge 30 to 90 centimeters underground, contained the primary electronics and instruments. The aftbody, which was designed to stay close to the surface, was aimed to collecting meteorological data and relaying data back to Earth using the orbiting Mars Global Surveyor spacecraft. Experience gathered during DS1-MFS was used to develop flexible junctions between the two segments.

Unfortunately, the two miniature probes (carrying ten experimental technologies each) failed to respond to communication efforts by NASA engineers. The problem is supposed to came from a wrong impact manoeuvre.

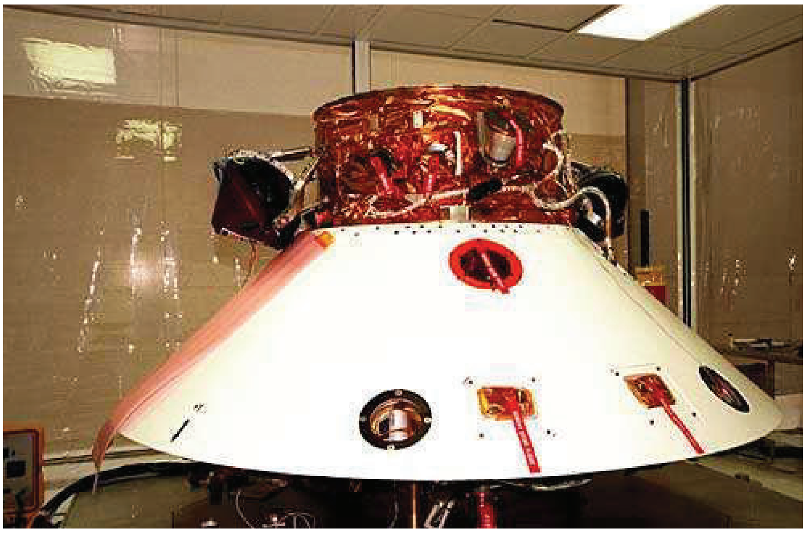

Figure 1.14: Two Deep Space 2 probes piggybacking onto the Mars '98 Lander Spacecraft.

1.3.4 Earth Observing 1 (EO1)

The New Millennium Program (NMP) Earth Observing-1 (EO-1) spacecraft (Year 2000) demonstrates multifunctionality with several technologies, namely:

- health monitoring hardware;
- carbon-carbon radiators;
- improved thermal coatings;
- flexible solar arrays.

Figure 1.15: Render of Earth Observing 1.

One of the objectives of this mission involved health monitoring and management. The objective of this technology is to develop on-board software that will automatically detect and diagnose failures in satellite's instruments and systems. Normally, troubleshooting is done on the ground. This kind of technology is also needed to provide the ability to troubleshoot the robotic systems required to handle increasingly complex tasks of exploration while they are millions of miles away from Earth.

Another key target was the demonstration of a carbon-carbon radiator. EO1 uses six passive radiators, each consisting of sandwich panels constructed with aluminum honeycomb cores. Five of the six radiator panels use standard aluminum facesheets. On the sixth radiator panel, as an EO-1 technology demonstration item, the aluminum facesheets were replaced with an experimental panel that utilized Carbon-Carbon (C/C) material for its facesheets (see Figure 1.16). The Carbon-Carbon Radiator (CCR) panel is a 28.62 in x 28.25 in sandwich composite panel with two 0.022 in thick C/C facesheets bonded to a 1 in 5056 aluminum honeycomb core with a density of 2.1 lb/ft^3 weighing approximately 5.5 lb. The facesheets of the panel are made of carbon fibers in a carbon matrix (two plies of P30X carbon fibers with carbon matrix established by Chemical Vapor Infiltration). The internal surface of the CCR panel is coated with an epoxy encapsulate to prevent particle contamination of sensitive instruments on board EO-1 and provide additional strength to the panel. The external surface of the CCR panel is coated with silver Teflon as required by the EO-1 spacecraft thermal design.

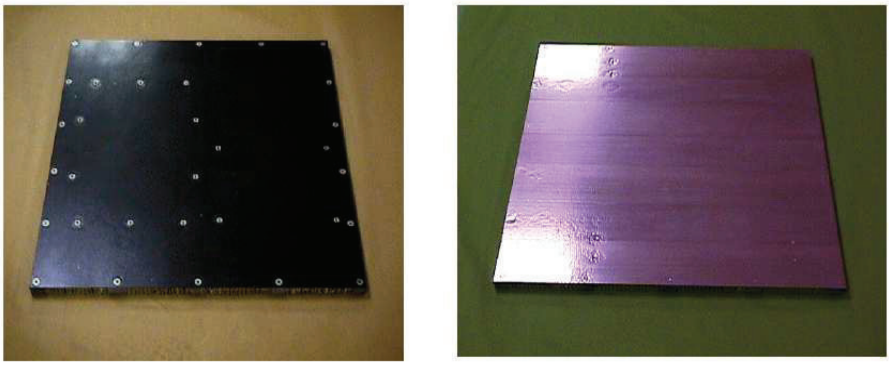

Figure 1.16: The C/C radiator replaces one of six structural panels on the EO-1 Spacecraft: it is both a radiator and a structural member. The exterior is coated with Silver Teflon for heat rejection.

The objective of this technology validation was to demonstrate that Carbon-Carbon could be a cost efficient facesheet material for honeycomb core radiator panels that also function as part of the spacecraft primary structure. Prior to spacecraft-level testing, the CCR panel was subjected to four thermal vacuum cycles. The CCR panel flight temperature measurements correlated extremely well with the predicted values obtained from the EO-1 spacecraft thermal model. The EO-1 mission has demonstrated that use of Carbon-Carbon facesheet material for fabricating honeycomb sandwich panels is a viable option for accommodating both thermally and structurally demanding application requirements into a single design.

In addition, another technology demonstration was to validate the thermal performance of an improved white thermal control coating developed by AZ Technology, Inc. The thermal control coating referred to as LA-II, is a low absorptance inorganic white paint. A low absorptance thermal coating will allow radiators to run cooler when exposed to an ultraviolet environment and thereby provide improved performance for space radiators. In general, the LA-II coating demonstrated

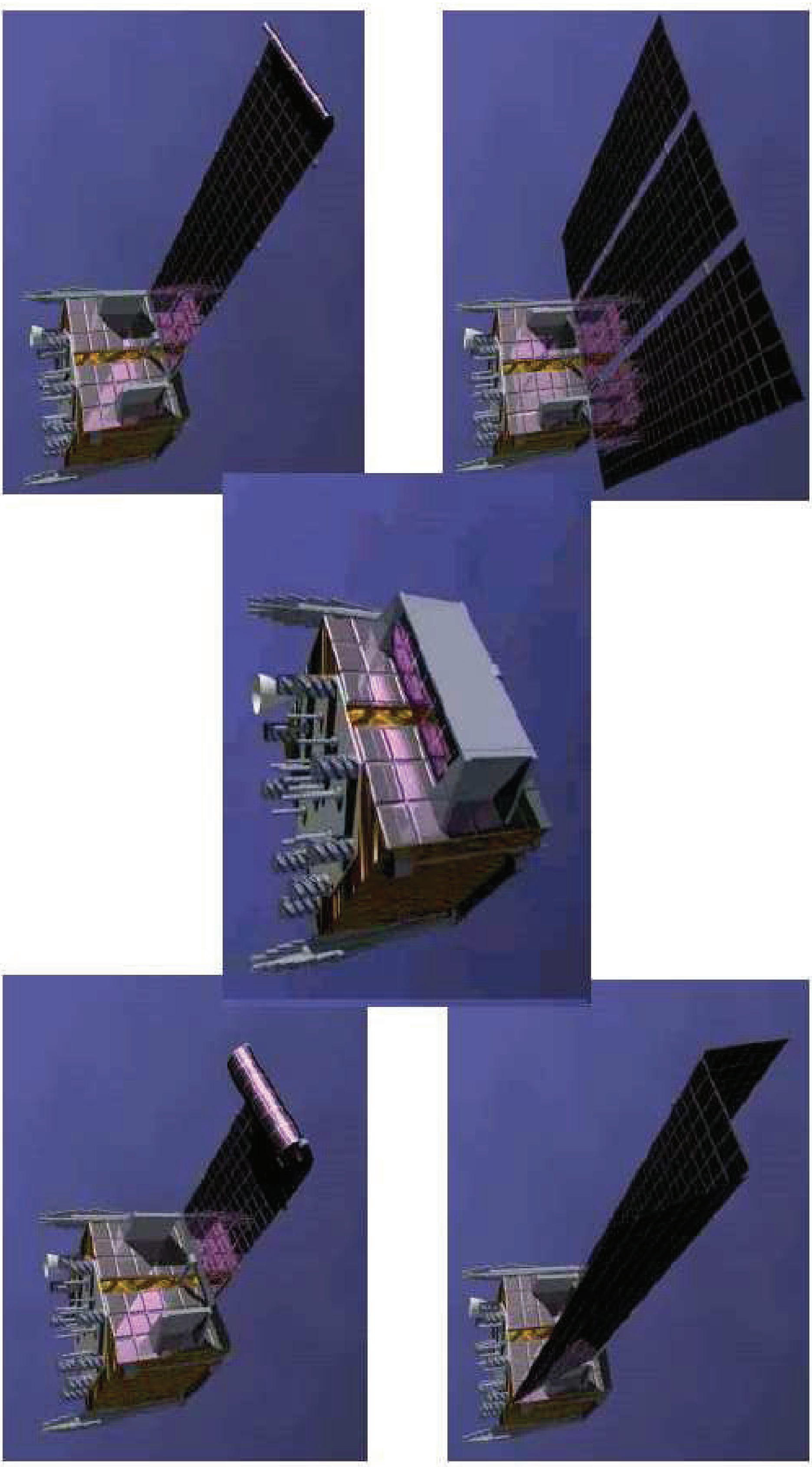

Figure 1.17: LFSA Rollout Array Concept for EO1.

and maintained a better α/ϵ than the Z93 after 12 months. The innovative paint also showed no appreciable property degradation. The LA-II coating has been subsequently selected as the baseline for the NASA SWIFT mission as a radiator coating.

Finally, Lightweight Flexible Solar Arrays, made of thin film CIS on polyimide, equipped with MFS cable and instruments were on-board EO1 (see Figure 1.17). The objectives of this technology were to increase science payload mass fraction by increasing array specific power to more than 100 W/kg and to demonstrate controlled deployment with the use of shape memory actuation (to release launch retention mechanism) followed by activation of shape memory hinges.

1.3.5 MightySat

MightySat, launched on the 19th July 2000, carried various unproven technologies for space test, among those was MFCBS, a multifunctional composite bus structure including power, thermal and structural functions.

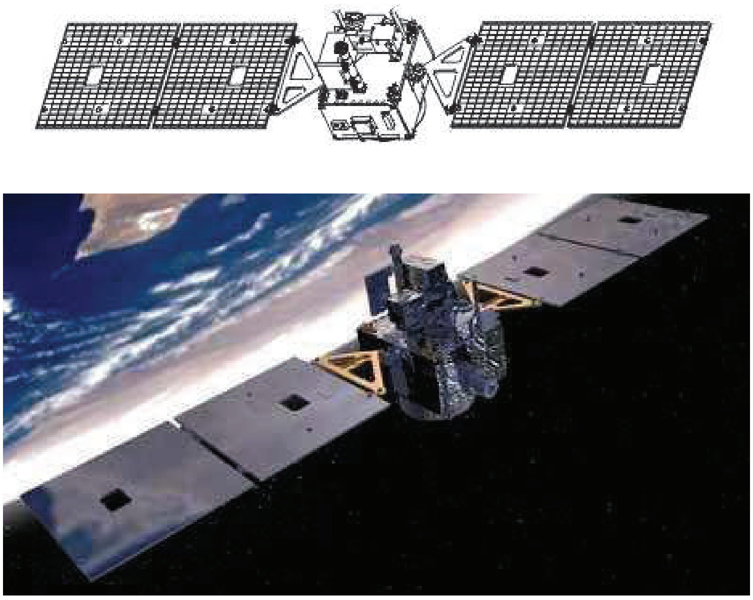

Figure 1.18: Mightysat.

The structure was made of high conductivity composite. The face sheets were made of carbon cyanate-esther laminate, and the core was made of aluminium. Carbon cyanate-esther doublers were attached to the structure to enhance the heat rejection, so that the spacecraft's structure replaced conventional radiators.

The structural panel performed thermal management: the thermal energy dissipated by the different subsystems was radiated and conducted to maintain the components in their operational range of temperature.

This design proved to operate as predicted and therefore embedding thermal control functions into the spacecraft's structure has been effectively demonstrated aboard this spacecraft.

1.3.6 Space Technology Research Vehicle-1d (STRV-1d)

Figure 1.19: STRV-1d.

STRV-1d was designed to prove various MFS technologies, in particular the capability of MF panels to protect equipment from radiation and thermal environment.

Provided that MFS eliminates external fairings for electronics, equivalent shielding is needed to minimize the adverse effects of the space radiation environment on the function of electronics. These effects include charging, single event upsets and part latch-up caused by high-energy protons and electrons. The shielding can be coated over or shaped around a radiation sensitive part. The shielding material may be a shaped metal or an adhesive matrix with embedded tungsten particles, which attenuate the radiation. The STRV-1d spacecraft carried a flight experiment to assess the feasibility of several suggested radiation hardened panels for future use as structural panels. In particular, Space Electronics, Inc. developed the RAD-COAT conformal shielding material in conjunction with NASA LaRC. The effectiveness of RAD-COAT has been validated in extensive laboratory testing simulating space flight and was carried as an experiment on the STRV-1d mission.

Moreover, the STRV-1d spacecraft's structure embedded electrical connections, and thermal management under severe thermal and structural requirements, as cryogenic hardware was attached to a thermally isolated subpanel of the MFS panel.

The spacecraft was launched in November 2000, but unfortunately it failed early, so that the results of the comparison between the different suggested designs for a radiation hardened composite are not known, and no data are available either about the structure's performance.

1.3.7 Advanced Technology Demonstration Spacecraft (ATDS)

The AFRL has been developing since 1998 a program called ATDS: Advanced Technology Demonstration Spacecraft.

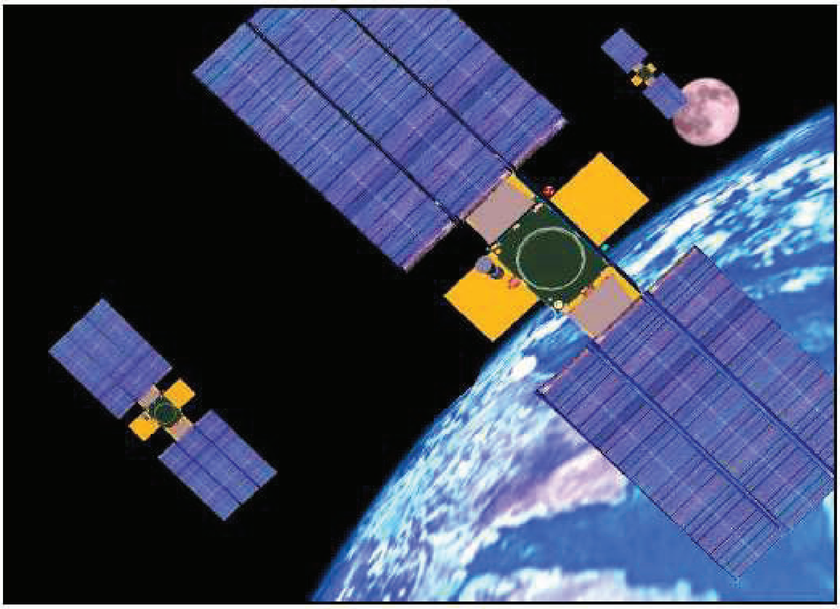

Figure 1.20: TechSat 21: three-satellite formation.

The aim of this program is to develop a protoflight spacecraft bus in order to space qualify it. It is to combine all the recent advances in techniques to reduce the total mass and volume of a spacecraft, including several types of MFS, among which the combination of structure, electronics, thermal management and radiation shielding.

The goal is to reduce the conventional 30 *kg* C&DH and power distribution subsystems of a small spacecraft to less than 3 *kg*. Onboard this spacecraft, the C&DH and power distribution subsystems are completely replaced by MFS panels.

This project is still under development, though the test phase has already been started. It is also a pathfinder for the TechSat 21 spacecraft.

TechSat21 is a micro-spacecraft project developed by NASA, the DoD, AFRL and LMA. Its design is to integrate the most advanced developments on MFS, including the type of MFS described for ATDS (embedded electronics, thermal control and radiation shielding). In particular, as in the ATDS program, the entire C&DH and power distribution functions will be undertaken by MFS.

TechSat21 was first planned to be launched in 2000. Nevertheless, this project is waiting for the ATDS experiment to be successfully achieved, as ATDS is its natural forerunner. Thus, probably, it will be launched within the next decade.

1.3.8 Lightpack

This is an activity focused on aeronautic aspects of multifunctional structures.

Lightpack project started in December 1996, with the aim to reduce avionic rack mass of at least 30%, thanks to new technologies, configurations, materials, structural design and manufacturing techniques.

Various alternatives have been explored in order to reach the goal, in particular:

- Metal Matrix Composites (MMC) with new casting and bonding techniques;
- Carbon Fibre Reinforced Plastic (CFRP) with plastic matrix.

Concerning CFRPs, only flight-qualified components were used, in order to obtain a process capable of certifying the structure after a reduced test campaign, in particular of those areas of the structure subjected to continued mechanical contact or frequent inspection (such as truss or panels). Various parts were connected via adhesives and rivets. CFRP components were also treated with a layer of epoxy resin.

To the structure was then added a further layer made of high conductivity material in order to obtain the proper EMC behavior.

Weight reduction achieved with CFRPs exceeds 45% with respect to conventional reference racks.

1.3.9 JPL research on Fluid Loop Based MFS

The thermal control challenges posed by small spacecrafts for future NASA science missions require advanced thermal control technologies. Both passive and active thermal control technologies are needed to enable or enhance future missions. In particular, near/far term microspacecraft missions require advanced thermal technologies.

In 2003, these reasons led the JPL to start a research branch on fluid loop based multi-functional structures.

The objectives are to:

- Develop a Multi-Functional Structure technology incorporating active thermal management, mechanical/electronic packaging and flex cabling and interconnect functions.
- Fabricate and assemble composite MFS panels for avionics, science payload, propulsion, radiator and fluid system pump assembly.
- Integrate MFS panels and demonstrate their performance in microspacecraft testbed.

1.3.10 JPL research on electronic-based MFS

Since 2003, the Jet Propulsion Laboratory started studying new concepts for the reduction of masses, volumes, power consumption and harness burden connaturated with electronic packages.

Significant benefit can be obtained incorporating in the design new high-density component packaging technologies and interconnection schemes. Nonetheless, a proper system packaging architecture can help reducing spacecraft volume and mass budgets, while increasing integration efficiencies, and providing modularity and flexibility to accommodate multiple missions while maintaining a low recurring cost. To address this necessity, JPL developed the Integrated Avionics System (IAS) [64], a novel system packaging approach with solutions that provide broader environmental applications, more flexible system interconnectivity, scalability, and simplified assembly test and integration schemes. This new avionic system brings low-mass, modular distributed or centralized packaging architecture which combines ridged-flex technologies, high-density COTS hardware and a new 3-D mechanical packaging approach, named Horizontal Mounted Cube (HMC).

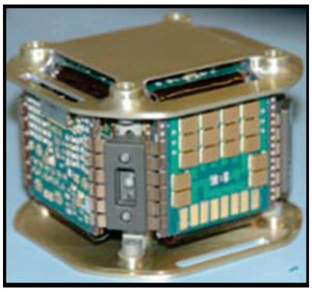

Figure 1.21: Integrated avionic cube [64].

The IAS is made up of a spacecraft structural panel, which integrates both the Horizontal Mounted Cube (HMC, which houses the command and data handling, power and attitude control electronics) and its network bus (which provides the system interconnectivity from the HMC to the spacecraft). Moreover, the structural panel is designed to provide thermal control and easy access to the backside of the network bus, for rework capability.

The proposed IAS communication architecture is based on a threefold bus. It uses PCI Bus to handle high-speed command and data handling, 1394 Firewire Bus to provide the high data rate for science data acquisition, and I2C Bus, as a low power solution used to accommodate power switching, pyro actuation, and temperature sensor interfaces.

The architecture was optimized to reduce the workload and shorten the development, integration and test activities. Interchangeability between engineering or flight subsystems provides flexibility for the system design teams to develop a spacecraft configuration independent of the avionics.

The IAS approach led to very promising results: from 49 to 63 percent reduction in mass, and from 71 to 86 percent reduction in volume.

Dynamics and thermal test were performed to ensure that the baseline packaging techniques were structurally sound, able to provide sufficient thermal dissipation, and to transmit electrical signals adequately based on flight predicted operating extremes. The dynamic and thermal environmental tests validated that packaging design can meet or exceed predicted performance. The in situ dynamics test results indicated no opens during the entire test duration, and the thermal vacuum test proved the HMC and IAS design could efficiently reject heat to an external environment.

A further development [65] in the direction of reduced masses and volumes was explored with the manufacturing of electronic circuit boards that can function as structural members within a subsystem, thanks to printed circuit board materials that demonstrate structural properties of strength and stiffness suitable for current spacecraft structural applications that require the use of aluminium and titanium.

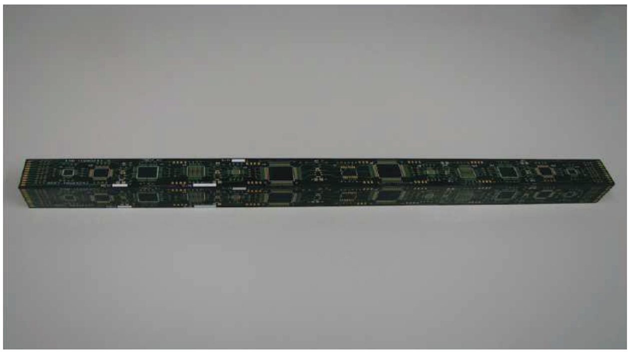

Figure 1.22: One of the box beam test articles assembled and ready for mechanical testing [65].

To improve the mechanical properties of traditional PCBs, they applied Carbon Core Laminates (CCL) usually incorporated as heat transfer layers. These layers can also be used as an electrical ground plane. In particular, the study used Stablcor, a proprietary material developed by Stablcor Inc. (ex ThermalWorks) and licensed to selected printed circuit board fabricators.

To assess the effect of CCL on mechanical properties, four different cross sections stacks were used: printed circuit boards with no carbon core laminate, 2 layers, 3 layers, and 4 layers of carbon core laminate. Four flat panels were connected along their edge to create a box beam structural member, thanks to a symmetrical square wave type edge (conceived to aid in the assembly process and maximize intersecting surface contact area) and structural adhesive cured in an oven to ensure maximum strength.

The specimens underwent three point bending flexural testing and cantilever mode flexural testing. The strength and stiffness were sensibly higher with increasing number of CCL layers, but the optimum strength and stiffness to weight ratio is achieved with a 2 layer construction.

This multifunctional PCB sandwich construction proved to be a viable structural element that can replace metallic design, showing that the goal of a strong yet lightweight electro-structural component is achievable, limited only by the dimensional limits of PCB production tools. A second phase of the task included the replacement of all metallic structural elements of an existing binocular vision space flight rover camera with a carbon core laminate structural approach.

This technology is a good candidate for super computing space borne applications, and for use in micro, nano and pico satellites.

The next step in the study of multifunctional electronical component was achieved with the application of CCL for improved heat transfer performance and solder interconnection reliability with respect to ball grid arrays and column grid arrays [66].

As can be seen in Figure 1.23, the test vehicles for this experiment were representative of a very common printed circuit board size frequently used in space electronics: a Compact PCI Bus standard card size of (6U).

There were three different types of printed circuit boards tested, identical in dimensions, but made of different layups. The first type was of standard polyimide and copper, with no CCL. The second type included two layers of ST-10 CCL placed symmetrically within the board cross-section. The third type included two layers of ST-325 CCL placed symmetrically within the board construction.

All test articles had an assortment of land patterns to allow placement of CGAs, BGAs, transistors, flip chip devices, and large resistors.

For the thermal vacuum test, the test vehicles were populated with only resistors, located with sufficient space between them in order to impart heat in a well distinct portion of the board. The resistors dissipated around 15W total. Infrared imaging was utilized to take a snapshot of the board at zero time and once every minute for 30 minutes.

The temperature profiles generated during testing indicated excellent thermal transfer results for the board incorporating CCL ST-325, which exhibited improved heat transfer over the printed circuit board type without CCL construction and the printed circuit board with ST-10 construction.

Figure 1.23: One of the test articles ready for thermal testing [66].

This study proved the ability of the CCL construction to enhance the flow of heat from a device source and distribute that heat more efficiently than a standard copper/polyimide-based solution. This result can open the way to a new benefit for space-related electronics: the ability to cool electronics more efficiently without increasing mass.

1.3.11 AFRL/MDA research on Flexible Circuits

As already mentioned, MFS technology is not only studied for space borne applications, but in the aeronautic industry as well, mostly for unmanned air vehicles (UAV).

Flexible circuits (copper clad polyimide) are an integral part of the majority of multifunctional structures, both in space and aeronautic applications. Although flexible circuits have found a wide acceptance in commercial electronics, their usage in flight hardware particularly in module-to-module interconnects has been almost non-existent. The primary reasons include lack of familiarity, minimal design rules, concerns with shielding systems and interfaces with standard circular and rectangular connectors.

Two wide programs are currently designing flight experiments for flexible circuitry and embedded integral shielding: SBIR and STTR[9].

AFRL and MDA have funded both an STTR Phase II and an SBIR Phase II to provide solutions to these problems and provide demonstration hardware and methodology. Key advantages of defense programs' use of this technology include large savings in cable mass and volume ($> 50\%$), cost savings through the elimination of touch labor, test point exposure through flex extensions at any location and the use of distributed active and passive components for data processing and sensors. The efforts in both the Phase I and Phase II tasks have focused on Northrop Grumman Global Hawk cabling systems and the Boeing Delta IV launch vehicle.

In the framework of SBIR program, a UAV's cable harness for power and data routing is being designed, as well as flexible circuitry for two flight experiments of the AFRL RESE program.

In the framework of STTR program, the cabling of the Boeing Delta IV vehicle is under development using flexible circuitry with integrated shielding[10].

1.3.12 MULFUN

In 2004, the European Commission (EC), within the Sixth Framework Programme (Priority 4) Aeronautics and Space, assigned a 3-year long STRP (Specific Targeted Research Projects) named MULFUN to an international team coordinated by INASMET.

The goal of the study was to develop advanced, integrated, lightweight components for airborne and space vehicles. The MFS concept is therefore the core of this activity that has been developed following various steps:

- exploration of the MFS state of the art;
- design, manufacturing and test of two demonstrator breadboards integrating structural, thermal and electronic functions (see Figures 1.24 and 1.25);
- design, manufacturing and test of an Active Phase Array antenna (see Figure 1.26);
- design, manufacturing and test of a power-electronic equipment housing (see Figure 1.27).

Thales Alenia Space - Italia was involved in MULFUN project, in particular concerning thermo-mechanical aspects and breadboards design of BB1 and BB2:

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[9] The U.S. Small Business Administration (SBA) Office of Technology administers the Small Business Innovation Research (SBIR) Program and the Small Business Technology Transfer (STTR) Program. Through these two competitive programs, SBA ensures that the nation's small, high-tech, innovative businesses are a significant part of the federal government's research and development efforts.

[10] Methods have been developed to provide a mix of shielding depending upon environmental and signal integrity needs.

these activities will be described more thoroughly, given their relevance to this thesis.

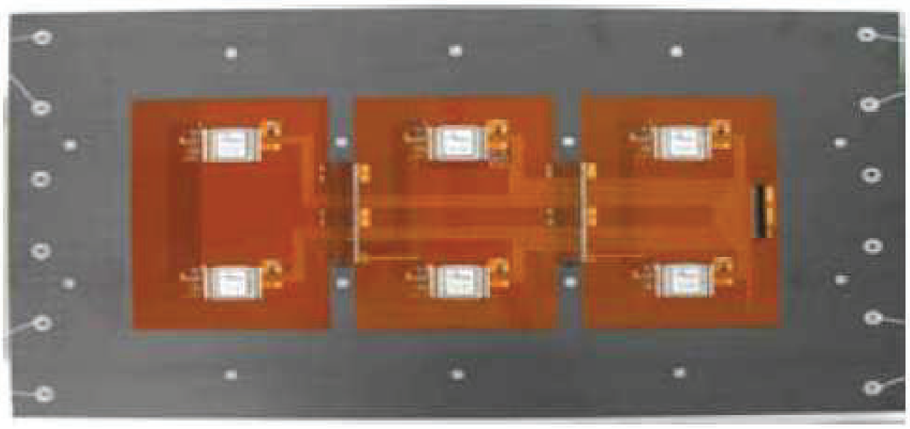

Figure 1.24: MULFUN BB1: multifunctional sandwich panel with surface-mounted electronics and passive thermal control.

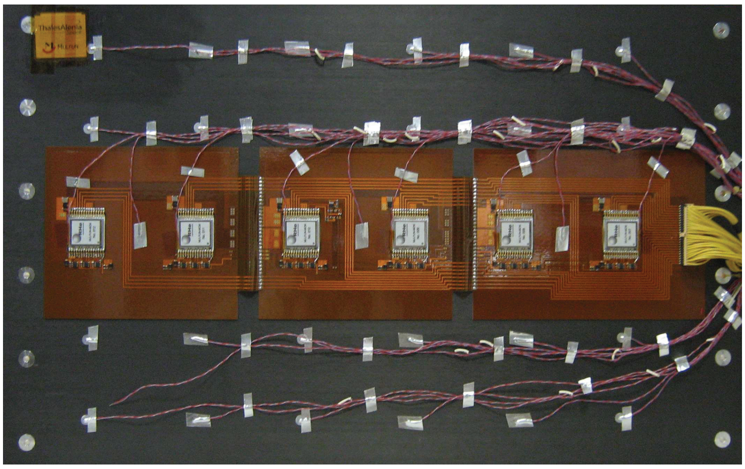

Figure 1.25: MULFUN BB2: multifunctional sandwich panel with surface-mounted electronics and active thermal control.

The development of BB1 and BB2 demonstrators in Thales Alenia Space Italia allowed to implement technologies that reduce the weight, increase the compactness, the reliability and decrease the size of the system.

For both breadboards, the proposed approach (high-conductivity skins with surface-mounted electronics), and a higher level of integration of the different functions (structural, thermal and electronic) yields mass minimization for the multifunctional structure and a simplification of the layout.

The innovation consists right in the combination of materials and technologies as well as in flat interconnection between the single electronic circuits and their integration in the structural panel.

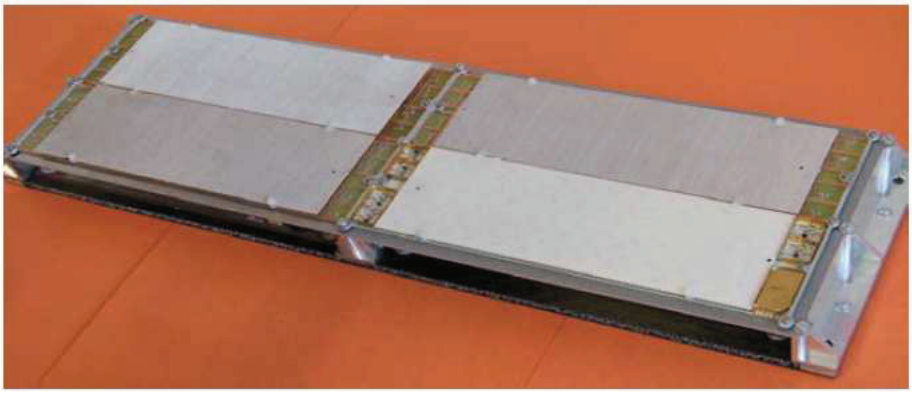

Figure 1.26: MULFUN BB3: multilayer phased-array antenna.

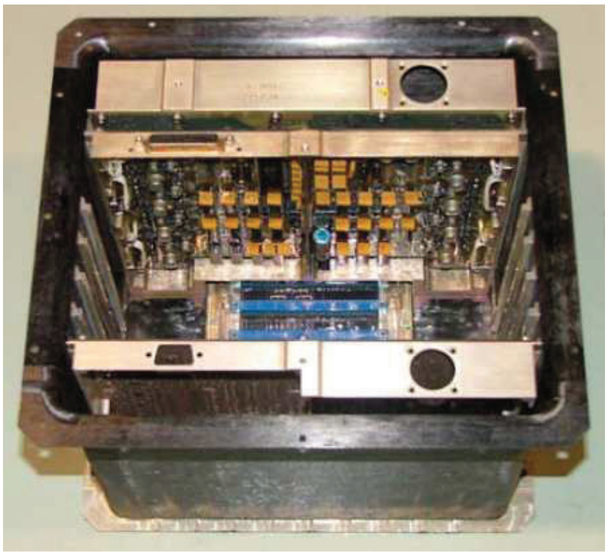

Figure 1.27: MULFUN BB4: power electronics housing based on high-conductivity fibres.

BB1: structural panel with passive thermal control

The objective of this research was the design, manufacturing and validation of a panel with integrated *passive* thermal control and mechanical/structural functions, providing accommodation and housing for flat and flexible electronics.

BB1 panel is a rectangular ($500\ mm \times 800\ mm$) sandwich construction with aluminium honeycomb and high-modulus Carbon Fiber Reinforced Plastic skins. Each face skin is made of 8 plies of K13D2U fiber in EX1515 cyanate ester resin, arranged in a quasi-isotropic layout (0, +45, -45, 90, 90, -45, +45, 0). The bending stiffness of the panel is ensured by a 20 mm thick aluminium honeycomb, type 3/16 0.001. The selected type guarantees a good compromise between stiffness properties and mass density. The panel is supported with 6 + 6 thru all inserts with a diameter of 17 mm, equally distributed on panel short sides and located 30 mm from the edges. The rigid and flexible electronic was bonded onto the CFRP skin.

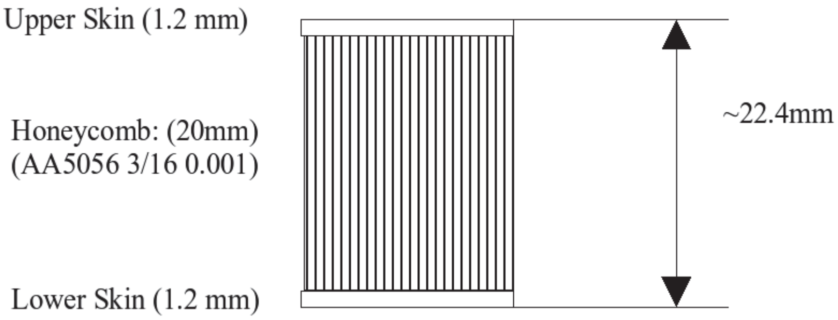

Figure 1.28: BB1 sandwich section.

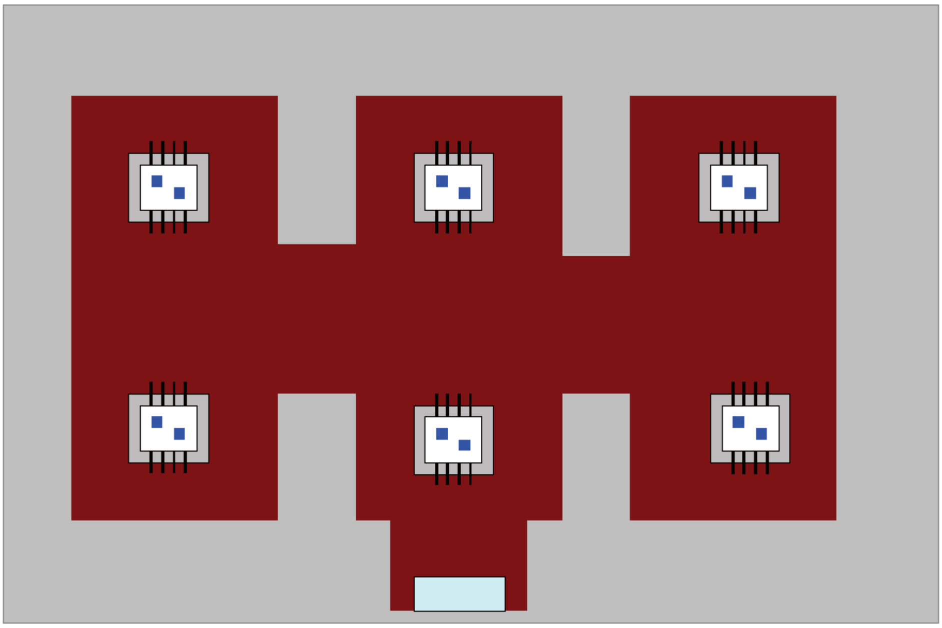

Figure 1.29: BB1 CFRP skin with mounted MCMs and rigid/flex boards.

Tests were performed for material characterization and testing of production steps (e.g. fibre volume fraction, tensile characteristics, CTE, insert pull out…).

The whole-breadboard manufacturing process was divided into three main steps:

- CFPR part manufacturing;
- manufacturing of mass dummies;
- assembly of bread board.

During the CFRP manufacturing, face sheets were created by using autoclave technology.

Mass dummies were built just for the mechanical tests and were mounted on the breadboard only during mechanical characterization phase; then, during breadboard thermal-vacuum campaign, masses were removed as they were not representative of real thermal load conditions.

The final integration of the breadboard was more complex and can be divided in the following steps:

1. bonding of sandwich panel parts (face sheets and core);
2. breadboard machining (edge trimming, holes drilling for inserts);
3. inserts application;
4. electronics bonding (rigid part and flexible part);
5. assembly and finishing of breadboard (mounting of mass dummies).

Mechanical and thermal tests were performed for the BB1. The mechanical test was a random vibration test, which was passed successfully. The thermal test was a thermal balance/thermal vacuum test, which was also successfully concluded.

The new approach for BB1 consists in the usage of high-conductivity CFRP face sheets for thermal management (besides the structural function) and in the direct application of advanced electronics (flat motherboard mounting MCM components) to those face sheets.

The development and verification activities confirmed that:

- manufacturing of the parts is possible;
- such a technology is suitable for applications in aviation and space;
- such a technology can provide higher performance with respect to traditional design concepts for electronic panels.

BB2: structural panel with active thermal control

In a complementary way with respect to BB1, the objective of BB2 research activity was the design, manufacturing and validation of a panel with integrated *active* thermal control and mechanical/structural functions, providing accommodation and housing for flat (flexible) electronics.

BB2 is very similar to BB1 (see previous subsection), but with a more stringent configuration of electronics (more concentrated power dissipation) and representative for active thermal control approaches.

BB2 is also a 500 $mm \times 800$ mm rectangular sandwich panel. To retain similarity with BB1, aim of the BB2 thermal control functions is to spread the heat across the panel, with the outer skin acting as a radiator. It was decided to embed miniature heat pipes into the panel. From a technological point of view, however, the solution is perfectly equivalent to the case in which a fluid loop (mechanically or capillary pumped) is integrated instead of heat pipes.

Optimum MFS-oriented design solutions for structural sandwich panels could be achieved thanks to a proper combination of high-performance plies (high-conductivity fibres), tailored composite layup and embedded thermal hardware. In particular, each BB2 face skin is made of 8 plies of K13D2U fiber (0.15 mm thickness) in Bryte Ex-1515 cyanate ester resin, arranged in the layup (0, +28, -28, 0, 0, -28, +28, 0).

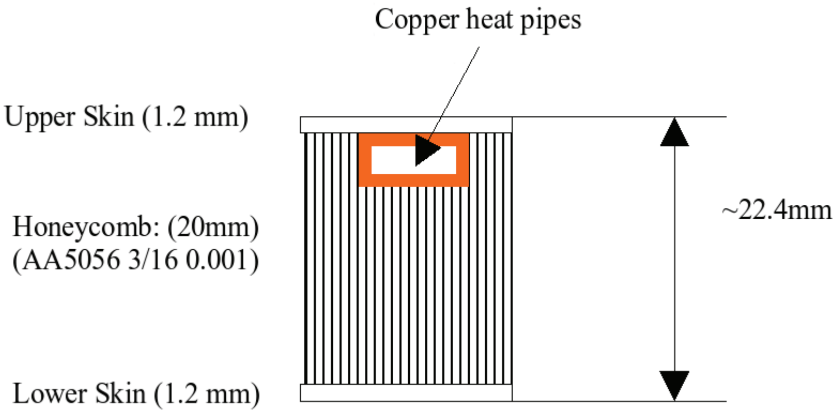

Figure 1.30: BB2 sandwich section.

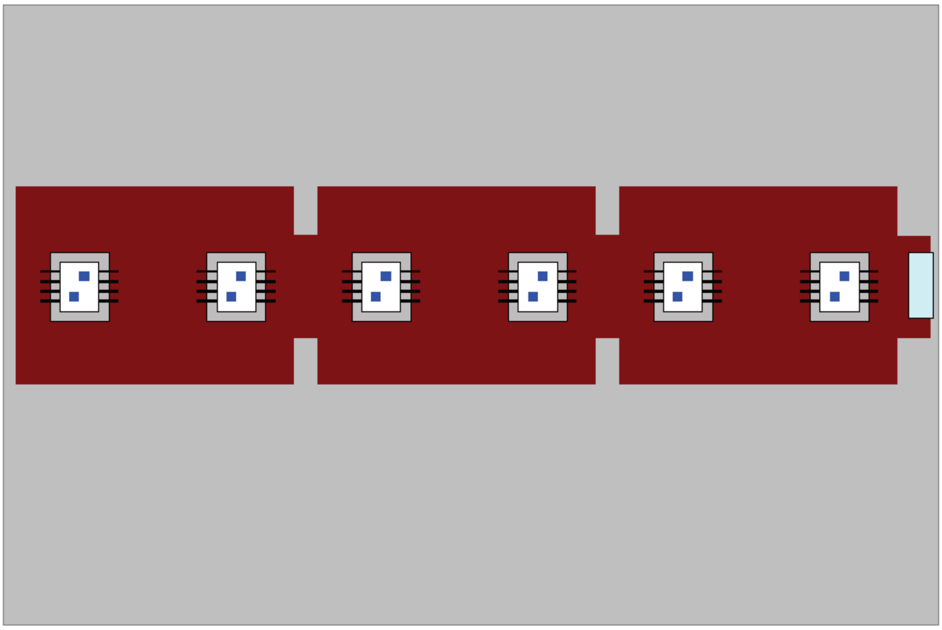

Figure 1.31: BB2 CFRP skin with mounted MCMs and rigid/flex boards.

Coupling between copper heat pipes and CFRP skins was critical due to CTE mismatch (which is a main concern especially when bonding long metallic elements to CFRP elements). A strongly anisotropic layup was therefore defined both to solve the problem and to enhance the thermal conductivity in the direction transversal to the pipes.

BB2, like BB1, had electronics mounted directly on the surface (see Figure 1.32). This electronics consisted of 6 MCMs and their flexible circuit bonded in linear distribution along longer side. The equipment is made of three rigid/flex motherboards with cut-outs for two ceramic MCMs each. Multi-chip modules mount bare dice and other components and have around 25 W power dissipation each (ca. 150 W power dissipation in total).

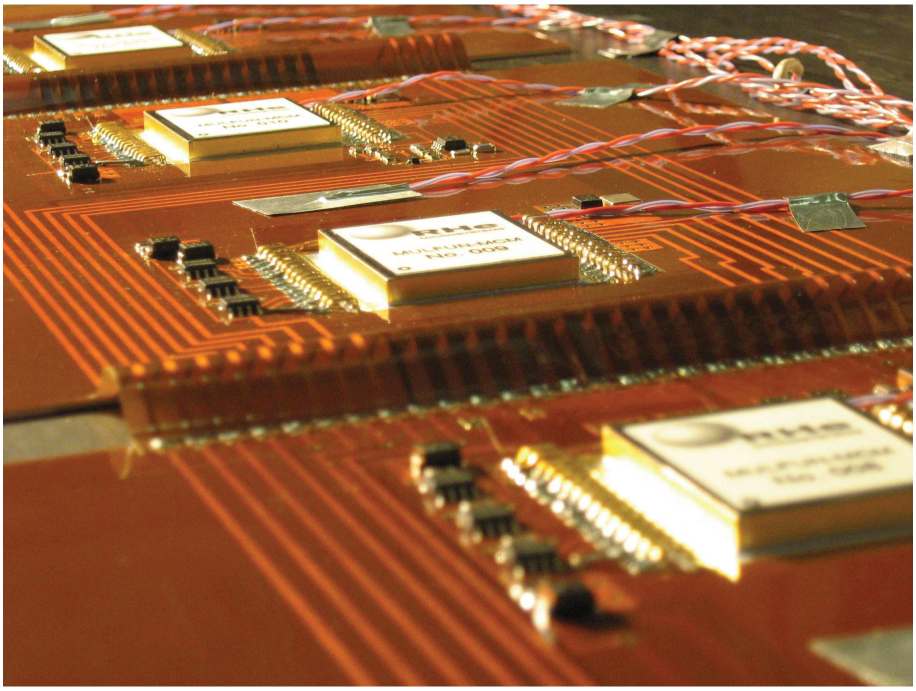

Figure 1.32: Close up of BB2 electronics.

The BB2 manufacturing process is very similar to the one of BB1. The main difference consists in the integration of miniature heat pipes, bonded under the upper skin.

The BB2 verification campaign was very similar to the one applied to BB1.

The development and verification activities confirmed that:

- manufacturing of the parts is possible;
- such a technology is suitable for applications in aviation and space;
- such a technology can provide higher performance with respect to traditional design concepts for electronic panels;
- with the active design (using heat pipes and a suitable layup) higher power dissipation and more critical power density figures can actually be managed with respect to the passive design.

1.3.13 ESA initiatives

The European Space Agency is promoting initiatives that aim to MFS study and development, in particular in the framework of GSTP-3 and GSTP-4 (General Support and Technology Programme 3 - 4).

The most recent GSTP-4 (Advancement of multi-functional support structure technologies) was entrusted to Spain and Germany: several partners were involved in the MULFUN study, with the main objective of reaching a detailed project of multifunctional structures to be validated.

A number of ITTs (Invitation To Tender) on technologies similar or related to MFS are often published by the Agency.

It is worth remembering that ESA Aurora Exploration Programme included a number of MFS-related activities. Besides the research for the embedding of hydrogen in structures, for example, there is also the concept of multifunctional integrated structures based on hollow spheres (such as the successful Atmospheric Re-entry Demonstrator).

Multifunctional integrated structures based on hollow spheres

Figure 1.33: Atmospheric Re-entry Demonstrator concept.

Within the Mars Sample Return (MSR) mission, it is foreseen to bring back to Earth samples of Martian soil. Those samples will have to be shipped onboard a dedicated probe that will go through the Earth's atmosphere following a hyperbolic interplanetary trajectory.

The entry conditions are of such a challenging nature that existing materials for heat shields will not withstand the generated heat fluxes (in the order of 8 to 10 MW/m^2). Besides, the probe configuration has to meet the requirements needed for a hard landing, which means touch-down speed of over 30 m/s.

In this context, there is a call for robust, lightweight, thermally insulating multifunctional structures. Indeed, these structures have shown highly attractive values of thermal conductivity. Their insulation properties are very well suited for an Earth re-entry application. In addition to that, they have a high absorption capacity due to their cellular structure.

This makes them a very good candidate for both a shock absorbing layer surrounding a sample container during a hard landing on Earth and meteorite and space debris protection panel material. Another interesting feature of such materials is their isotropic mechanical behavior. Thus, they can be used as load-carrying materials.

Composite Technology Studies

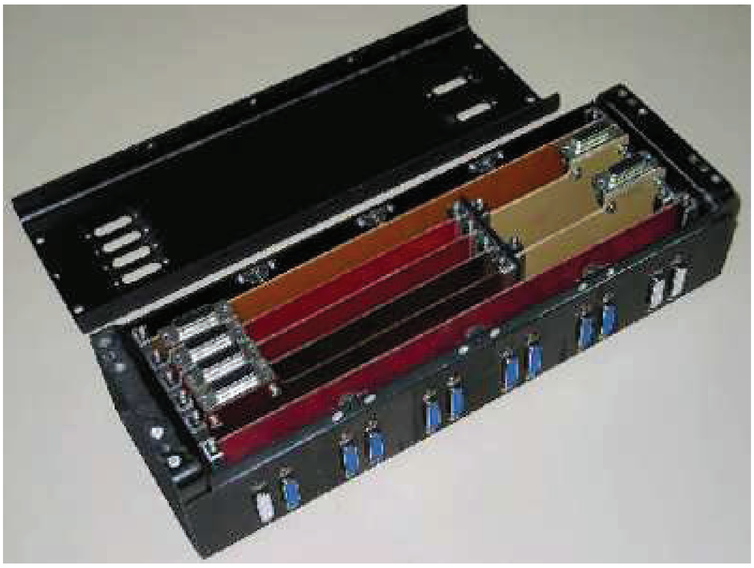

Figure 1.34: CFRP electronic box.

In ESA is ongoing the development of multi functional enclosures for payload boxes.

This is a mid-way concept of multifunctional structure that does not eliminate the electronic housing but add several tasks to its primary goal of retaining and protecting pieces of equipment.

Concepts were investigated in which the electronic enclosures for space applications provide multifunctional properties for structural integrity, heat management, radiation and particle shielding and should be lightweight. With the selected CFRP fibres (K1100, M40J) most of these design requirements could be fulfilled: structural, thermal and lightweight.

The mass reduction for a demonstrator housing was about 60% compared to a usual housing made of aluminum. This reduction could be achieved due to lower density, higher stiffness and higher directional thermal conductivity of the CFRP material. A further advantage of the CFRP housings is that they could be easily integrated in a supporting CFRP structure without any serious CTE mismatch.

1.3.14 TAS-I Demonstration BreadBoard (DBB)

The thermo-mechanical Demonstration BreadBoard is a sandwich construction based on the use of high-conductivity CFRP materials and embedded mini heat pipes. It is very similar to the second MULFUN breadboard, but was entirely produced in-house, while BB2 experienced external manufacturing.

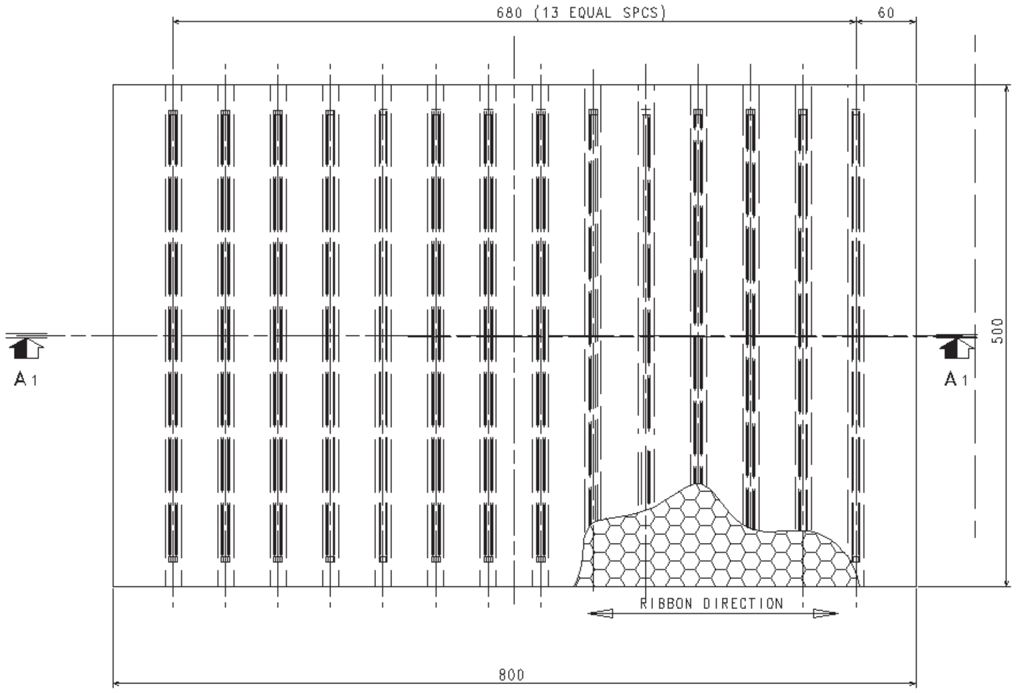

Figure 1.35: DBB top view.

The physical layout of DBB is represented in Figures 1.35 and 1.36. It is a 500 mm × 800 mm sandwich panel

The panel has 14 Cu-H2O type heat pipes bonded on the inner surface of the upper skin (each HP has a 8.5 mm D section and is 450 mm long). Heat pipes are fixed on the inner surface of the upper skin, equidistant from each other and parallel to the short side of the panel (y direction of local axes), placed in milled grooves (section of 10×10 mm, 480 mm length)created in the aluminium honeycomb in the direction parallel to the short side of the panel.

The thicknesses and materials of the skin and core remained unchanged with respect to BB2.

Regarding materials, the experience with DBB brought some interesting issues.

High thermal conductivity CFRPs[11] have, of course, advantages and disadvantages. Possible problems are their fragility, their high cost and the difficulty to obtain them from external producers. However they have many noticeable pros, such

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[11] Traditional structural carbon fibers have low thermal conductivity and often are rather good thermal insulators. On the contrary, high conductivity carbon fibers can reach up to $K_x = 1100\ W/m/K$ in the longitudinal direction. This value is very high when compared with aluminium thermal conductivity $K = 220\ W/m/K$. However, the composite matrix is polymeric and this material has values of thermal conductivity typically in the order of unity. Therefore the polymeric matrix is the main cause of reduction of thermal performance.

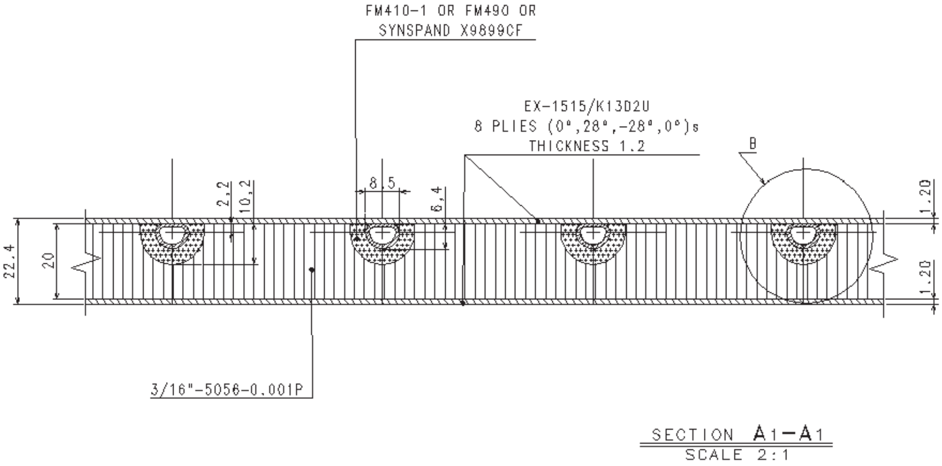

Figure 1.36: DBB section.

Table 1.2: DBB panel main features.

Feature	**Value**
Dimensions	500 × 800 × 22.4 *mm*
Skin fiber	Mitsubishi K13D2U
Skin resin	Ex-1515 cyanate ester
Skin thickness	1.2 *mm*
Skin layout	(0, +28, -28, 0, 0, -28, +28, 0)
Core material	Aluminium honeycomb
Core thickness	20 *mm*
Core type	3/16 0.001P
Heat pipes number	14
Heat pipes layout	Embedded, parallel to short side
Heat pipes materials	Cu and water
Heat pipes length	450 *mm*
Heat pipes section	8 *mm* diameter, D shaped
Heat pipes type	Anti gravity
Heat pipes supplier	CRS

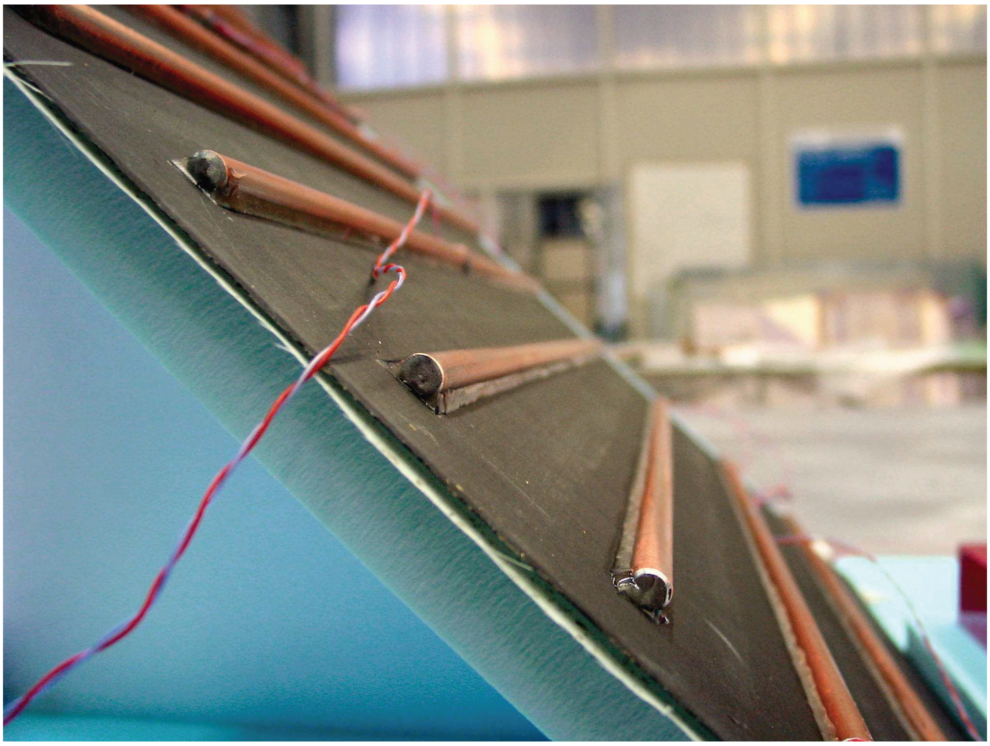

Figure 1.37: DBB upper skin with heat pipes bonded.

as high dimensional stability, thermal conductivity values higher than aluminium[12], tailorable properties anisotropy[13]. These positive characteristics made them an eligible choice for DBB skins, which were made of 8 plies of K13D2U Carbon fiber (of which 4 almost aligned in the direction perpendicular to the longitudinal axis of the heat pipes) and embedded in polymeric matrix (Cyanate Ester). K13D2U fibers are just slightly less conductive with respect to K1100 fibres, but are much less expensive. These fibers are pitch carbon ones that undergo a high temperature treatment, called graphitization. The result of such a treatment is that the carbon percentage in the material reaches levels over 99% and amorphous carbon is changed into graphitic allotropic state. This creates extremely strong covalent C-C bonds and a very ordered structure, presenting a preferential orientation of planes in the longitudinal direction of the fiber. Parallel atomic plans are held together by Van der Waals interactions and are therefore responsible for the anisotropy of the structure. In fact the thermal conductivity of the fiber is excellent in their longitudinal direction and low in their transverse direction[14]. A second reason that led to the choice of this material is the low density of K13D2U. This enables the production of thin and light structures, well suited to become skins for sandwich panels.

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[12] E.g. quasi-isotropic K13D2U skin has $K_{xy} > 225\ W/m/K$.

[13] E.g. skin lay-up (0°,±28°,0°) has $K_x = 400\ W/m/K$, $K_y = 50\ W/m/K$.

[14] The most important characteristic that was considered for DBB skins was thermal conductivity. Like all graphitic fibers, K13D2U has a thermal conductivity that steeply decreases below $-110°$C. That property reaches a maximum around $-40°$C and presents a slight decrease above 25°C. Therefore, the interval in which the longitudinal thermal conductivity is reasonably higher fits well with the operational temperatures typical of space applications.

The fiber structure allows for the following properties:

- high strength-to-weight ratio;
- high mechanical strength;
- low coefficient of thermal expansion.

On the other hand, the EX-1515 resin brings the characteristics hereafter reported:

- low density;
- remarkable resistance to radiation;
- low moisture absorption;
- low outgassing values;
- good resistance to microcracking when exposed to repeated thermal cycling.

Panel integration, thermal balance/cycling tests, model correlation and NDI inspections were carried out in-house. Given that the most relevant fraction of test conducted on DBB is of thermal type, then the choice was made to equip the panel with thermocouples embedded into the structure from the very first steps.

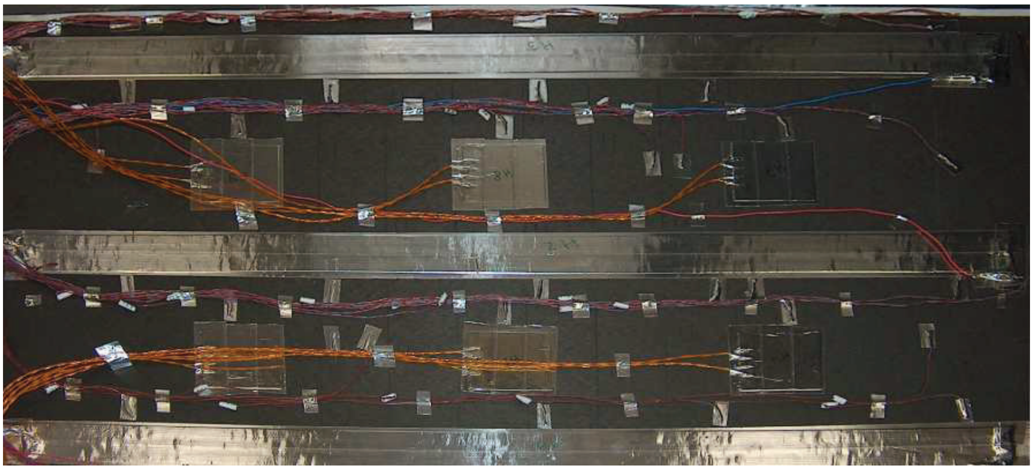

Figure 1.38: DBB instrumented for thermal test.

DBB was useful in building expertise in MFS structures, their design and their production. In particular, the demonstrator was effective in pointing out technology and process related problems.

Inaccuracies occurred in the integration of the panel, in particular in the heat pipe/skin bonding process (and this led to non-uniform and non-optimized thermal coupling with slight performance reduction). This made it clear that such a process needs care and shall be optimized and qualified in view of its application to programs.

Moreover, with DBB there was an increased difficulty in TMM correlation due to non-homogeneous panel characteristics.

Despite the manufacturing imperfections, test outcomes were satisfactory:

- heat pipe/skin connection was able to accommodate thermal stresses with no disbonding nor performance degradation after TB and fatigue tests;
- heat rejection capability was still above the design goal (300 W/m^2 with skin at 60°C maximum temperature and concentrated power dissipation layouts);
- analytical trade-offs[15] showed interesting potentiality of the technology (up to 40% mass reduction) and gave inputs to the design of an Advanced Breadboard (ABB).

Moreover, the demonstrator proved the effectiveness of the design with heat pipes embedded in the panel. This solution leaves the external skin surfaces completely free from thermal hardware, thus enabling a more flexible placement of surface-mounted units or a modification of equipment layout even during advanced phases of the design process[16]. Furthermore, embedment of heat pipes eliminates the need for baseplates. This innovative layout gives therefore the possibility to obtain fairly standard panels that can be used in various projects without having to change or design ex-novo a different solution for every new application.

After DBB experience, a great number of trade-offs were conducted, in order to compare traditional and MFS-oriented design solutions. The aim was to identify fields of applicability and constrains of the concept while quantifying benefits.

Five test cases were pointed out:

- elementary module of a typical radiator panel for spacecrafts;
- MFS Demonstration Breadboard (representative for a distributed-electronics configuration);
- SICRAL 1B SVM (typical low power density S/C panel);
- SICRAL 1B PLM (typical telecom S/C panel);
- COSMO SkyMed SVM.

Analyses were based on TMMs of the reference configurations, keeping into account the following variables:

- skin and core material;
- heat pipes type and positioning;
- box dimension;
- power dissipation.

while relevant parameters to assess the performances of the configurations were:

- power density;

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[15] Trade-offs were based on real S/C radiator configurations and DBB test results.

[16] Nowadays, on the contrary, thermal and structural design have to be re-drawn every times a major change in equipment or payload layout occurs.

- heat rejection capability;
- mass;
- complexity.

Thus, the various configurations evaluated different materials (for skin and/or core) and heat pipes type and positioning. Moreover, the suitability of different solutions to increasing power density applications was assessed.

In general, the conclusions were the following.

Materials Using CFRP and C/C skins leads to better performance (and the higher the power density, the higher the performance improvement). In particular, substitution of Al skins with high-k CFRP and use of embedded mini heat pipes yields significant mass saving (up to -40%). Furthermore, substituting CFRP skins with C/C ones significantly improves the heat rejection capability, especially in case of lower power density. Higher Z-axis (face-to-face) conductivity of C/C makes it possible to remove heat pipes with less power loss with respect to CFRP skin cases. In case of high power dissipation, however, C/C panels allow moving HPs to the outer skin, but there is no possibility to completely avoid using heat pipes.

In case of extremely high power dissipation, substitution of Al skins with high-k CFRP and use of embedded mini heat pipes is not enough to provide the required heat rejection capability. Remarkably, it was determined that use of C/C sandwich can lead to the required thermal performance with 35% mass saving.

Heat pipes Heat pipes are necessary in cases of medium-high power densities (even with CFRP skins). In order to obtain higher heat rejection while trying to minimize mass penalty, it is better to augment heat pipes number instead of increasing skin thickness. Moreover, cross heat pipes can be used in order to spread heat across the whole radiative area in transverse direction when composite CFRP skins do not provide an equivalent transverse conductivity. When using CFRP layers, moving HPs to the outer skin lets the internal skin completely free from thermal hardware, improving design flexibility with no performance loss. The only alternative capable of avoiding the use of heat pipes is C/C sandwich.

Layout In case of configurations like dense TWT banks, it is difficult to avoid mounting the units directly on heat pipes. Use of high-k CFRP is not sufficient to allow the substitution of heavy external hardware with embedded mini heat pipes. However, in most cases, simplification of the layout can be achieved, providing cost and schedule reduction for drawings and integration and higher design flexibility (which in turn may allow the optimization of electronic layout and performance improvements).

1.3.15 TAS-I Proto-ABB demonstrator

During year 2008, the activities on the ABB demonstrator were already going on, but the carbon-carbon honeycomb sandwich supplier, Ultracor, underwent several difficulties with materials and production process. These problems caused an enormous delay in the deliver of the C/C panel for ABB.

Since internal research program could not be stopped with zero results and since two M.S. and one Ph.D. Theses were working on this activity, there was a slight change in the design. The choice was made to integrate the electronics on the DBB substrate, to test assembly process, verify items' performances and reliability and validate the new concept of One-Wire sensor network.

the following items were installed on the rear of the MFS DBB panel:

- one left motherboard, integrated with its components;
- one left Dallas Cable, integrated with sensors.

For details on the support panel, see the previous subsection dedicated to DBB, and for details on the electronic equipment, see the ABB section in the chapter dedicated to design and manufacturing. Additional information on design, manufacturing and testing of Proto-ABB can be retrieved in [7].

1.4 Contextualization of research activity

After this general overview of current trends and activities in the MFS field, it can be useful to contextualize and justify the work with respect to previous studies.

Literature review shows that the research activity presented in this thesis was already called for 30 years ago, when studies [1] based on collection of mass data from dozens of scientific satellites determined that more or less 64 percent of the total spacecraft dry mass is concentrated in the two technology areas of structure and packaged electronics (see Figure 1.39). The same studies, highlighted the necessity of advances in materials, integration, design, and miniaturization of electronics as technology thrust areas that could yield significant mass reductions for future spacecraft programs. More recently, a critical review of the same data [64] stressed the relevance of increasing subsystem integration under the structural, electrical, component packages, and thermal point of view.

Current trend in spacecraft design is towards smaller, lighter and higher performance satellites (e.g. higher power densities), therefore leading to the need of reducing cost and providing added value by integration of functions. Looking at the different efforts undertaken by space business stakeholders all over the world, it is clear that the ability to reach an high level of integration among different subsystems in a single multifunctional structure is an essential innovative technology to face future space missions.

Moreover, many research project ([3], [67], [68], [69] among others) show a trend toward distributed multifunctional systems, in which miniaturization of electrical and electronic components allows adding new capabilities to a structural component with minimum mass burden.

Up to 2010, TAS-I had a good previous knowledge and expertise in the MFS field thanks to two research projects conducted in synergy with each other:

- Advanced Thermo-Mechanical Systems For High-Dissipations Management, which is an internal research project.

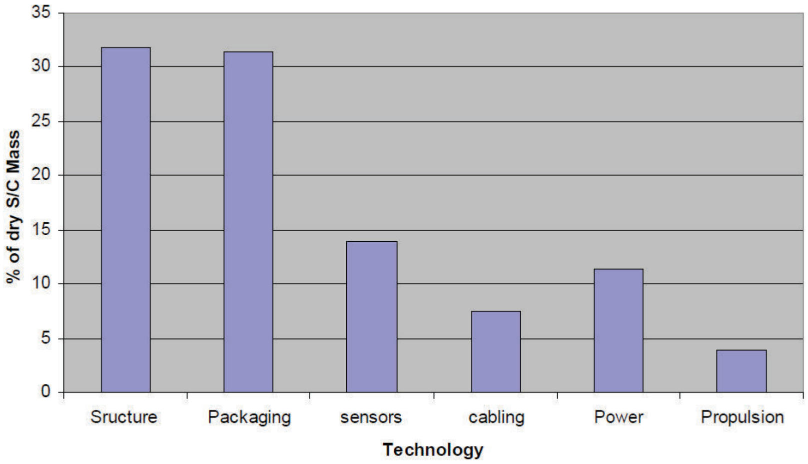

Figure 1.39: Spacecraft dry mass distribution by technology area, obtained by analysis of mass data regarding all JPL interplanetary spacecrafts over a 22 year period.

- MULFUN (Multifunctional Structures), which is an STRP from the European Commission.

The first research program on the development of Multifunctional Structures, named Advanced Thermo-Mechanical Systems for High Dissipations And Health Management, started in 2005 and was mainly devoted to the assessment of a number of studies and the development of technologies that, besides being suitable to integration in a multifunctional structure, are also useful to enhance global spacecraft performances. General objective of the activity was to develop the capability of designing and manufacturing lightweight multifunctional structures through innovative solutions and integrated design concepts[17]. The research activity was aimed at the integration of structural, thermal, electrical, shielding and diagnostic functions in a single structure, based on advanced materials and components.

The second project, named MULFUN, was an STRP of the European Commission (Sixth Framework Programme[18], FP6) devoted to the development of lightweight, fully integrated, advanced equipment for aircrafts and spacecrafts. MULFUN has been coordinated by Inasmet and aimed to the development and test of two demonstrators. TAS-I actively participated to MULFUN project and developed its own demonstrator.

Within these two projects, three breadboards integrating the structural, thermal and electrical functions have already been designed, manufactured and successfully tested (BB1, BB2 and DBB). A fourth advanced demonstrator (ABB) was under development in 2010, additionally covering the integration of monitoring functions via distributed sensor network and/or embedded fiber optics.

After MULFUN project was completed, TAS-I was looking forward to carry on the research activity, perhaps in the FP7, and two other programs were open in the meantime for the study of multifunctional systems:

- Integrated Multifunctional Systems, which is an internal research program.

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[17] Great importance is given to integrated design and manufacturing processes/tools.

[18] The EU's Framework Programme for Research and Technological Development is a major tool to support the creation of the European Research Area.

- STEPS, which is a research program funded by the European Commission and managed by Regione Piemonte.

The trade offs conducted in TAS-I after the DBB experience justified the choice to proceed with the study of Carbon-Carbon materials, and the ABB project was started.

Based on its strategic view, TAS-I was willing to explore mainly 4 aspects of MFSs:

- **Advanced Thermal Control**, including
  - high- or anisotropic-conductivity materials;
  - embedded thermal hardware;
  - integrated smart devices;
  - distributed thermal management;
- **Lightweight Structures**, including
  - advanced composite materials;
  - metal or carbon foams;
  - smart composite structures;
- **Advanced Electronics**, including
  - surface-mounted devices;
  - flexible circuitry;
  - embedded circuitry;
- **Other Functions**, including
  - diagnostic/control systems;
  - radiation and EMI/EMC shielding.

Therefore, in 2010, when the work described in this thesis started, the choice was to pick certain areas within the aforementioned list, and deepen the study in those directions. The selected areas were: flexible circuitry, embedded thermal hardware, integrated smart devices, diagnostic/control systems, distributed thermal management, and advanced Carbon-Carbon materials with high thermal conductivity.

The first goal was to complete the work on the ABB demonstrator, with its integration and testing activity. A second goal was to carry on the development of STEPS project, from the design phase to the final prototype verification. A third goal was to look for additional opportunities to expand the research in the MFS field. This objective actually led to the acquisition of a funding opportunity under the FP7 (beginning of the ROV-E program), and to the development of an akin study in collaboration with the Jet Propulsion Laboratory. A fourth goal was to introduce a multidisciplinary approach in the design and analysis of multifunctional systems.

To our best knowledge, nobody else is addressing the same architecture of multifunctional systems that is under study at Thales Alenia Space Italia, and this represents an opportunity of technical and commercial advantage. All the previous discussion shows the reason why Thales Alenia Space Italia endorsed this research activity with its study programme on Integrated Multifunctional Systems.

Chapter 2

Design and Manufacturing

2.1 Technology selection

2.1.1 Flex and rigid flex electronics

In space satellites, electronic boards are built with materials like Duroid and FR4.

Duroid is a registered trademark of Rogers Corporation. It is a non-metallic composite material, i.e. ceramic reinforced PTFE (Teflon), used as a microwave circuit substrate.

FR-4 is a composite thermoset plastic material made of woven fiberglass cloth with an epoxy resin binder. It has good strength to weight ratios and near zero water absorption. It is known to retain its high mechanical values and electrical insulating qualities in both dry and humid conditions. It is flame resistant (self-extinguishing). It is most commonly used as an electrical insulator for a wide variety of electrical and mechanical applications.

These materials are thermally and chemically robust; they have a high melting point, good thermal conductivity (around 0.35 W/m/K) and low thermal coefficient of dielectric constant (circa +7 ppm/°C from -50 to +150°C). Moreover they have low outgassing characteristics, and good resistance to radiation damage, especially in an oxygen-free environment such as space.

These qualified materials can still be suitable for multifunctional systems, especially when tailored with embedment of carbon-based layers (see subsection dedicated to Stablcor). Unfortunately, traditional PCBs, thick films (on ceramic), and Direct Bond Copper (DBC) are all technologies which restrict circuit and package designs to two-dimensional boards. The one potential pathway into the third dimension is through the use of multilayers, but this approach becomes increasingly difficult with each additional layer added beyond the first, and is typically a cost prohibitive high performance solution. One of the applications discussed in this thesis, the JPL μRover system, is in fact aiming at demonstrating the feasibility of MFSs based on conventional rigid electronics.

However, a radical way of overcoming the limitations of traditional rigid substrates is to resort to other materials, ordinarily used in industrial applications, but not so common in space applications. In fact these material could allow exploitation of the third dimension, adaptability to odd geometries, introduction of static- and dinamically-flexible applications.

Since flex electronics is studied for usage in many engineering fields, ideally, a good substrate would present a unique balance of properties that would make it suitable for all applications. However, there is still no perfect material and compromises must be made: nowadays the choice of substrate depends on the final application. In order to choose a good raw material, it is mandatory to consider multiple important properties.

The most obvious physical trait for a flexible substrate is, of course, flexibility. This means that the substrate must be able to bend while not cracking or losing its other properties. There are applications in which bending only once is sufficient, while in other cases the substrate should repeatedly bend without significant long-term degradation. Along with being able to flex, the material shall be robust, and in particular it shall not stretch. Unfortunately, the ability to bend is often difficult to isolate from the ability to stretch. Just to mention, there are some modern applications (e.g. wearable electronics) which are raising the demand for stretchable substrates that easily deform under planar stress without hampering the functionality of the circuit. If in conventional flex (non-stretch) electronics it is assumed that the inorganic layers within the system are themselves thin enough to bend, in flex-stretch applications horizontal deformation of the substrate could cause the inorganic layers to crack. This problem can be overcome with odd shapes of conductor traces or, in the next future, with advances in conducting polymers (eliminating the need for inorganic materials).

Besides resistance to external stresses, internal stresses are also relevant: in particular, thermal stability is a primary concern. This is because of a threefold reason. First of all, thermal stability is important for fabrication aspects. Even if low-temperature PCB production techniques are under investigation, the substrate shall be able to survive conventional production/integration techniques (e.g. soldering) and therefore it is required to withstand reasonable processing temperatures without degradation. This means that both the glass transition temperature and the melting temperature of the substrate must be sufficiently high. Secondly, operating temperatures may undergo significant changes when the device goes through power cycles. Additionally, there are certainly applications in which a very large range of operating temperatures is desirable. In these cases, also normal device operations can play a significant role in thermally stressing the device. Last but not least, the coefficient of thermal expansion must be either sufficiently low or reasonably matched with those of the inner inorganic layers and of external supporting structures (if any). If the film expands or shrinks in an uncontrolled way, cracks, delaminations and de-adhesions are very likely to happen.

Just to complete thermal considerations, it is worth mentioning that the substrate will be asked to exhibit good thermal conductivity if high performance electronics are ever to be made flexible. Heat dissipation through the substrate without aid from an external heat sink would be the ideal method for heat extraction in flexible electronics, because of their thinness and possibly large surface area.

Another relevant substrate property is permeability, in particular to oxygen and water vapor. Usually, under this point of view, inorganic materials offer good performances, while polymers struggle to match the barrier properties of the former. It important to mention that some niche applications may on the other hand require semi-permeable substrates to allow sensors to operate (consider for example medical devices). However, an impermeable substrate is more versatile, because, if permeability is desired, pinholes can easily be engineered into it.

In many applications, especially those with very thin components like TFTs, it is imperative that the surface of the substrate be planar.

At the same time, it is also necessary for the support material to have good adhesion with other deposited layers and to be resistant to solvents and chemicals (this aspect is important both for etching processes and for harsh operative environments). In certain cases, if the final product shall not operate under chemically aggressive circumstances, the problem can be solved with temporary protective layers which may be deposited on the substrate before critical production steps.

Since displays are a major driving force in development of flexible electronic systems, opacity is a big deal: there is a need for optically transparent substrates for light emitting devices. In some cases (i.e. LCD displays), besides having adequate clarity, the substrate should not exhibit birefringence (index of refraction is dependant on the polarization of the light). This aspect is not so relevant in the smart skin case, nonetheless it is worth considering it. A transparent smart skin which leaves a visible back-structure could be useful in applications on SC outer surfaces or during AIT steps.

A final mention shall be given to cost. While flexible electronics undoubtedly offer a precious variety of new design options to users, they are also interesting because of the possibility of significantly reducing production costs. The real savings of flexible electronics comes from the ability to operate in a roll-to-roll scheme, because this allows for a continuous stream of devices to be produced virtually without interruption. This benefit is dependant on the ability to cheaply produce large rolls of substrate, and on the ability to effectively and continuously readjust the production process to the inevitable alignment issues that arise from the quickly running substrate.

To summarize, an ideal substrate must be flexible (of course), physically and thermally stable, thermally conductive, impermeable, smooth, adhesive, chemically inert, transparent, and economically viable.

Commercially, a number of substrates are available as the raw material for the design of flexible electronics: not only can we rely on a great variety of polymers, but also on metals (e.g. passivated stainless steal), minerals (e.g. mica), glass and even simple paper.

Glass meets nearly all the requirements of a flexible substrate. It is both physically and thermally stable and a suitably high melting temperature can be achieved. The CTE is low (around 3 ppm), extremely close to that of silicon. Glass is an extremely good barrier. It has water vapour penetration levels on the order of 10^{-12} g/(m^2 day) (so low it is nearly immeasurable and can essentially be considered zero). Glass also has excellent surface properties and can be easily polished if necessary (roughness can be kept under 1 nm RMS). Glass is also highly resistant to most chemicals. Unfortunately, it is difficult to produce very large sheets of glass that are thin enough. In fact, glass only becomes flexible with thicknesses below 200 microns. Films as thin as 30 microns can be produced, but their usefulness is limited by narrow width and reduced surface smoothness. Moreover, with reduced thickness the price increases, and glass is not suitable for roll-to-roll processing. These combined effects make glass a less than ideal substrate for use in flexible electronics.

Metal films also satisfy many of the aforementioned requirements. They can be produced in large rolls and they have a very high modulus of elasticity (e.g. 200 GPa for stainless steel), therefore they are very unlikely to deform and very well suited in roll-to-roll processing. The CTE is usually higher than silicon or glass (15-20 ppm for stainless steel), but still compatible with requirements of electronic assemblies. Metals have a sufficiently low permeability (stainless steel is considered completely impermeable) and can be worked to meet surface planarity requirements. As a consequence of all these good properties, metal substrates have already been integrated into first generation flexible displays, even if the major drawback with a metal substrate is that it is completely opaque, and thus unsuitable for transmissive displays.

Polymers have a long curriculum of use in microelectronics because they offer multiple advantages over traditional materials. The principal motivation for incorporating polymers into electronics is their low cost. Moreover they are lightweight and particularly suitable for roll-to-roll processing because of their ability to be highly flexible. All these characteristics can help keeping low per unit cost of very large volume production (an aspect of great relevance for the birth of truly disposable flexible electronics). Beyond this, they are easy to process and can be engineered to have a wide variety of properties such as high melting temperature, high strength, or high optical transparency. Unfortunately, it is as yet impossible to combine all the desired properties into a single polymer. Many polymers are affected by melting temperatures far below those used in traditional electronic processing: since the maximum temperature that the substrate is processable at is typically much lower than its melting point, it becomes impossible to deposit the device layers on it (when the polymer passes its glass transition temperature it typically becomes too stretchy). Although specialized high temperature polymers do exist and exhibit spectacular stability, they do not meet any of the other requirements we have mentioned up to now (in particular, they lack flexibility and transparency). Advancements in processing methodologies can solve the problem. While temperatures for modern silicon processing surpass 1000°C, new techniques such as laser processing can reduce required temperatures to as low as 150°C. This is still a fairly high value for many polymers, however it is accommodating enough that this class of materials can be considered a viable solution for flex electronics.

Low dielectric constant is a crucial property of the substrate as interconnect density increases. As space between conducting lines shrinks, inductance and crosstalk become problematic, but these problems can be mitigated with lower dielectric constant materials. Polymers are becoming the dielectric materials of choice because their low dielectric constant allows higher packaging densities, faster transmission speeds, and lower power consumption.

Perhaps, the major disadvantage of polymers is their susceptibility to humidity and water absorption. This is a characteristic that must be carefully considered, because it poses a serious problem for the reliability of flexible electronics. In many cases exposure to oxygen and water will lead to long-term failure, while in some particular applications failure is almost instantaneous. As an example OLEDs are very demanding: they need values lower than 10^{-5} ml/(m^2 day) for oxygen and lower than 10^{-6} g/(m^2 day) for water, at 40% relative humidity, while LCD technology is more forgiving and requires only 10^{-1} g/(m^2 day) for water. For most polymers, permeability does not exceed 0.30% water absorption, which translates to good dimensional and electrical stability under variable humidity conditions. In many cases this is an acceptable value, while for more demanding applications (e.g. flexible displays) barrier layers (such as a thin Al or oxide layer) can be added to polymer films.

As an example, General Electrics has developed a ultra high Lexan®barrier film for organic electronics [71], a field where permeability requirements are five orders of magnitude more stringent than those applied to food packaging. This film is effective against moisture and molecular oxygen (see Table 2.1).

In general, permeability and adsorption heavily affect outgassing properties. Materials used for space systems shall be selected based upon low outgassing criteria, e.g. those based on micro-VCM test[1]. Outgassing behavior can be described by means of the following parameters:

- Total Mass Loss (TML), i.e. the difference of mass directly before and after vacuum test.
- Collected Volatile Condensible Material (CVCM), i.e. the mass gain of the test collector plates divided by the initial mass of the tested material.
- Recovered Mass Loss (RML), i.e. the difference between initial mass and mass after re-conditioning (shows the amount of non-water products).
- Water Vapour Regained (WVR), i.e. the amount of water uptake after vacuum test.

The general requirement for materials outgassing is RML $< 1.0\%$ and CVCM $< 0.1\%$. The Water Vapour Regain (or release) (WVR) can be calculated as WVR = TML - RML. The TML data for water absorbing materials such as polyamides, polyimides and polyurethanes is often above 1.0%. Water absorption is in most cases reversible and can be controlled by purging of critical hardware with dry gases. Often the water absorption of materials is not harmful with respect to contamination. Materials with high TML outgassing, but acceptable RML (RML $< 1.0\%$) and acceptable CVCM (CVCM $< 0.1\%$) may be accepted for the normal cases where the following considerations are applicable:

- No equipment at temperatures below -100°C is involved (no cryogenics).
- The material's water desorption is fast (e.g. in case of polyimide films and polyurethane paints).

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[1] Volatile Condensable Material (VCM) is defined as the weight of condensate obtainable at 25 °C in a given interval of time from a unit weight of a thin sample of material maintained at 125 °C in a vacuum of at least $5 \cdot 10^{-6}$ torr. The micro-VCM techniques has been established as a procedure for rapid screening of polymeric samples of the order of 100 milligrams for maximum VCM content and total weight loss.

Table 2.1: Summary of characteristics of ultra-high barrier Lexan®.

Property (units)	**USDC Specifications**	**GE Lexan®Performance**
Moisture Barrier	10^{-6} g/m^2/day	low 10^{-5} mid 10^{-6} (at 23°C 50% RH)
Chemical Resistance	acid, solvent, alkali	Pass
Electrical Conductivity	$\geq$40 Ω/Sq	40.3 Ω/Sq
Optical Transparency	>80%	82%
Mechanical Flexibility	bend around 1 in radius	Pass
Thermo-Mechanical Stability	2000°C for 1 hour	Pass
Adhesion	$\geq$4B	4B
Dimension stability	<20 ppm/hr at 150°C	4 ppm/hr
Average surface roughness	<5 nm	0.6 nm

- No high voltage equipment is involved.
- Dry gas purging can be used to control the water re-absorption during ground life up to launch.

However, in the space field, a component made of permeable materials must usually be baked out before integration and flight, to avoid both dimensional damage (e.g. during soldering) and chemical contamination. Other mitigation techniques, such as application of protective coating or shielding, can be applied in order to avoid or remove residual, process or handling contaminants.

The CTE for polymers is typically much higher than that of inorganic materials (roughly 1 order of magnitude); however for organic circuitry the CTE does not pose a problem. Despite these inevitable tradeoffs, there are multiple polymers that are useful in certain areas of flexible electronics.

Last but not least, plastic substrates are of great interest, because flex polymer technology employs industry standard manufacturing processes (i.e. etching and surface mount reflow), but at the same time offers lower cost and higher performance solutions. They allow to fold or roll the final product, and with a proper planar shape they can accommodate unique geometrical configurations. Another intrinsic advantage of flexible polymer substrates is their ability to integrate passive thick film components into the design at a low cost (refer to subsection on inkjet and silkscreen printing).

Published work [70] has demonstrated the feasibility of this low cost alternative solution. Integrated power modules, which utilize Kapton flexible polymer substrates in conjunction with both surface mount and bare dice components have been fabricated and tested. A volume reduction of approximately 25% was achieved between the classical PCB version and the initial flex circuit, while the second flex circuit with SMD and bare die approach displays a volume reduction of approximately 54% from the first flex, and an overall volume reduction of 66% from the PCB package (see Figure 2.1).

Three out of four applications (ABB, STEPS, ROV-E) in this research activity are focused on polymer-based flexible electronics. It is therefore useful to center the attention on three categories of polymers: polyesters, polyimides and liquid crystal polymers (LCPs).

Usually low end products are based on polyethylene terephthalate (PET), while high value, high reliability products are printed on polyimide (PI). Polyethylene naphthalate (PEN) is a cost effective film with performance between that of PET and PI.

Flexible polyester dominates the low performance, high yield electronics market. Its widespread usage is due both to its simplicity and low cost, and to acceptable electrical, chemical, and mechanical properties. The largest disadvantages of polyesters are their inferior thermal performance as compared to polyimides, in particular under the CTE point of view. In fact, polyesters tend to shrink under higher temperatures, although there are some formulations with a maximal 0.1% dimension change up to approximately 150°C. A classical example is the Bo-PET (Biaxially-oriented polyethylene terephthalate) known under the tradename of Mylar. A comparison between two semi-aromatic polyesters, PET and PEN, is given in Table 2.2.

Table 2.2: Comparison between PEN and PET.

Property (units)	**PEN (Teonex®Q65FA)**	**PET (Melinex®ST506)**
Upper temperature for processing (°C)	180 ÷ 220	150
Glass transition (°C)	120	78
CTE (ppm/°C)	1000	1000
Shrinkage in MD at 150°C after 30 mins (%)	0.05	0.1
Youngs Modulus at 20 °C (GPa)	5	4
Youngs Modulus at 150 °C (GPa)	3	1
Haze (%)	0.7	0.7

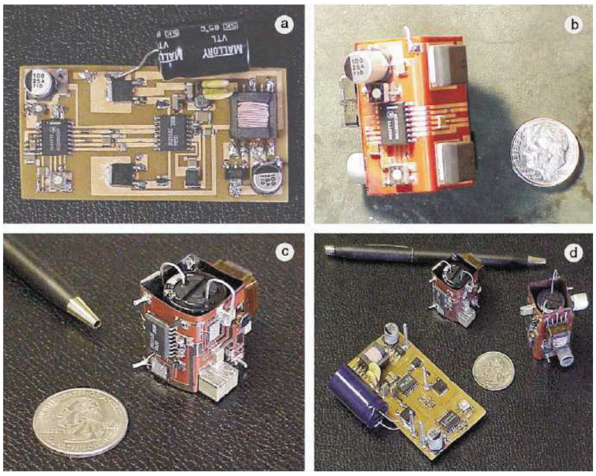

Figure 2.1: In [70], three fully functioning prototype designs are described. The first prototype uses an FR-4 PCB substrate and surface mount technology, the second prototype uses a flexible polyimide substrate and surface mount technology, while the third prototype utilizes a flexible polyimide substrate and surface mount in conjunction with bare die technology.

Polyimides are slightly more expensive with respect to polyesters, but still cost effective. They are high temperature substrates; they are strong, solvent resistant, easy to process, and environmentally safe. The films are produced in rolls and can be worked (bent, folded, formed) after circuit processing due to their resistance to fracturing. Polyimides are most often used with copper circuitry, though they are also highly suitable for polymer thick film (PTF) processes. A classical example is the para-amid (portmanteau word for para-aromatic polyamide) known under the trade name of Kapton.

Liquid crystal polymers (LCPs) are a class of aromatic polyester polymers. Typically LCPs maintain a high mechanical strength at high temperatures. Their mechanical and thermal properties are as good as that of commonly used substrate materials for circuit cards, or better (stiffness, strength, coefficient of thermal expansion, conductivity): mechanical properties are such that they could be used as a structural components as well as an ideal substrate material, in applications such as UAV wing structure.

LCPs can be manufactured as a laminate, but they also have the advantage over classical polymers to be thermoplastic and therefore they can be injection molded, with none of the waste associated with the usual epoxy (thermoset) electronic packaging plastic materials: they can be reworked to be shaped as desired. Compared to common substrates such as Teflon or polyimide, LCPs have a very high melting temperature, so that the material can withstand the high temperature processes used for manufacture and assembly, such as soldering and bonding. They can be welded, though the lines created by welding are a weak point in the resulting product.

Liquid crystal polymers also exhibit low in-plane CTE values, but tend to have a high Z-axis coefficient of thermal expansion.

Another natural trait of LCPs is radiation hardening, the ability to withstand significant doses of radiation without degradation of physical properties.

Thanks to their extreme chemical and physical resistance, LCPs are exceptionally inert. Of course, they have good weatherability. They resist stress cracking in the presence of most chemicals at elevated temperatures, including aromatic or halogenated hydrocarbons, strong acids, bases, ketones. Their hydrolytic stability in boiling water is excellent. LCPs are highly resistant to fire, since they have inherent flame retardancy. Environments that deteriorate the polymers are high-temperature steam, concentrated sulfuric acid, and boiling caustic materials. LCPs also exhibit natural hydrophobic properties, therefore they have a very low moisture absorption coefficient, of the order of that of glass. So, they maintain the electronics components in a stable and dry environment (being nearly hermetic is highly desirable to keep the electronic components in their optimal operating conditions).

All in all, LCPs are an exceptional barrier against harsh chemicals and environments, which have an adverse effect on circuits or chips. NASA Langley Research Center succeeded in producing a LCP formulation that, laminated in 4 mil film was able to maintain zero leakage over >24h permeation test with 25 psi Helium gas at room temperature [74].

LCPs are available in film thickness down to 1 mil. They can be laminated to copper down to 9 microns and they are compatible with sputtering processing, allowing copper thickness of 6 microns or less. This makes them one of the thinnest dielectric materials available. Companies such as Foster-Miller or Glenair are using these desirable electronic packaging traits to offer LCP-based packages to the commercial and military electronic markets. A classical example of LCP is the commercial aramid known as Kevlar.

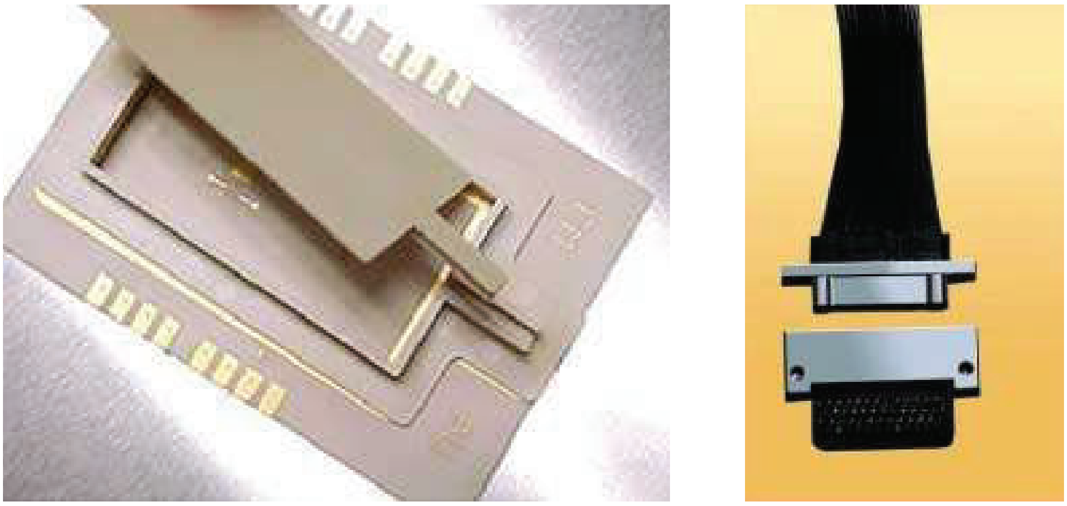

Figure 2.2: On the left, a Forster-Miller electronics package; on the right, a Glenair connector. Both equipments are based on Liquid Cristal Polymers.

Table 2.3: Comparison of selected properties of base polymeric materials for PCBs (both rigid and flex).

	FR-4 standard	**Polyimide**		**Polyester**		**LCP**
		Adhesive	**Adhesiveless**	**PET**	**PEN**	
Tg (°C)	135	250	220	75	125	170
Minimum use temperature(°C)		-125	-125	-60		
Maximum use temperature (°C)	140	200	200	105	180	> 250
Coefficent of thermal expansion @22°C (ppm/°C)	15	20	20	25	20	17
Change in linear dimensions @100°C, 30 min (%)		<0.3	0.04 to 0.02	<0.5		
Dielectric strength @ 1 mil thickness (V/mil)	750	6000	6000	3400		3500
Volume resistivity (ohm-cm)	3e13	1e16	1e16	1e16		1.3e13
Dielectric constant	4.7	3.4	3.4	3	2.9	2.8-3.0
Loss tangent	0.020	0.005	0.005	0.005	0.004	0.003
Moisture uptake (%)	0.15	~1.2-3.0	0.8	0.3	1	0.02-0.1
Typical thickness range (mil)	>2	0.5 to 5	1 to 6	2 to 5	1 to 3	1 to 2
Tensile strength @25°C (psi)	45000	25000	50000	20000 to 35000	30000	31000
Break elongation (%)		70	50	60 to 165	110	
Tensile modulus @25°C (100000 psi)	3	4.3	7	5		3.58
Tear initiation strength (lb/in)		1000	700 to 1200	1000 to 1500		
Tear propagation strength (g/mil)		8	20	12 to 25		
Resistance to strong acids	Good	Good	Good	Good	Good	
Resistance to strong alkalis	Fair	Poor	Good	Poor		
Resistance to grease and oil	Good	Good	Good	Good		

Table 2.3: Comparison of selected properties of polymeric flex circuit base materials.

	FR-4 standard	**Polyimide**		**Polyester**		**LCP**
		Adhesive	**Adhesiveless**	**PET**	**PEN**	
Resistance to organic solvents	Good	Good	Good	Good	Good	
Resistance to water		Good	Good	Good	Good	
Resistance to sunlight		Good	Good	Fair		
Resistance to fungus		Non nutrient	Non nutrient	Non nutrient		
Time to delamination @260°C (min)	>60	>60				
Time to delamination @288°C (min)	10	>48				
Moisture absorption after 700 hours, 17-30°C T, 30-70% H (%)	0.2	0.45				
Tg after moisture absorption (°C)	115	180				
Time to delamination @260°C after moisture absorption (min)	7	12				
Time to delamination @288°C after moisture absorption (min)	3	10				

The selection of the most suitable material is based upon the comparative evaluation of a number of properties.

The glass transition temperature (Tg) is the temperature at which the coefficient of thermal expansion in a resin system makes a sharp change in rate from a slow rate of change to a rapid rate of change. The glass transition point can also be detected by a sudden change in heat capacity or viscosity. A high Tg is important in order to assess the maximum temperature of production processes and, especially for PCBs that are very thick, to guard against damages during the soldering operations.

The coefficient of thermal expansion (CTE) is the relative change in dimensions that the base material undergoes when heated. It is a relevant property for a couple of reasons. First of all, when production steps, surface-mount assembly processes, or power spikes during operations subject the PWA to temperature shocks, a CTE mismatch between different layers can lead to delaminations or can induce stresses in the copper sheets. This poses a functional reliability concern. Moreover, if the FPCB is attached on a certain supporting structure, mismatches in CTEs can lead to detachments somewhere in the structure-adhesive-PCB stack.

Relative dielectric constant (ε_r) measures the effect that a dielectric has on the capacitance between a trace and the surrounding structures. This capacitance affects impedance as well as the velocity at which signals travel along a signal line. Higher ε_r produces lower impedance, higher capacitance, and lower signal velocity.

Loss tangent or dissipation factor (tan f) is a measure of the tendency of an insulating material to absorb some of the AC energy from electromagnetic fields passing through it. Low values are important for RF applications, but relatively irrelevant for logic applications.

Electrical strength or dielectric breakdown voltage (DBV) is the voltage per unit thickness of an insulator at which an arc may develop through the insulator itself.

Water absorption factor (WA) is the amount of water an insulating material may absorb when subjected to high relative humidity, expressed as a percent of total weight. Absorbed water increases relative dielectric constant as well as reduces DBV.

A summary and comparison of selected properties of polymers for flexible electronics is given in Table 2.3, together with values typical of FR4 as a term of comparison.

Flexible laminates can be made with different kinds of adhesives, Table 2.4 explains some characteristics of the main available formulations.

2.1.2 Inkjet or silkscreen printed electronics

For the preparation of printed electronics nearly all industrial printing methods are employed, and almost any solution-based material has been used, including organic semiconductors, inorganic semiconductors, metallic conductors, nanoparticles, nanotubes, etc. In this context, two different technologies are particularly interesting for the production of printed circuits (and in particular, resistors): inkjet printing and screen printing. Both can be applied either in sheet-based or in roll-to-roll approach.

Table 2.4: Typical adhesives for FPCBs (copyright Atotech Deutschland GmbH).

Adhesive	**Tg (°C)**	**Moisture absorption (%)**	**Remarks**
(FR) Acrylic	$30 \div 40$	$4 \div 6$	This is the standard adhesive for flexible printed circuit boards because of the relatively low cost and their ease of processing. Acrylic adhesives have a higher resistance to soldering conditions that polyesters and modified epoxies.
(FR) Polyester (PET)	$90 \div 110$	$1 \div 2$	PET adhesives are used in applications where there are no extremes of temperature or forces that will significantly stress the circuit.
Epoxy	$90 \div 165$	$4 \div 5$	Modified epoxies are generally less flexible than other adhesive systems but they can be modified by the addition of other polymers. They possess excellent resistance to high temperatures and modified grades offer excellent bond strength and material compatibility
Polyimide	$220 \div 260$	$1 \div 2.5$	PI adhesives have a very low coefficient of thermal expansion, which makes it a good choice for use in demanding multilayer circuits.
Phenolic Butyral	N/A	N/A	This is a special adhesive that has some application in selected areas.

Inkjet printing creates the layout by propelling droplets of ink onto a substrate. It can operate on a variety of substrates: paper, polyimide, polyester, PET, FR4, GX-13, glass, alumina, carbon fiber… This method offers low throughput of around 100 m^2/h and low resolution (ca. 50 μm). Typical trace thickness is between 50 and 500 nm, but there are two different solutions to achieve thicker tracks: materials can be chemically over-plated (suitable for reel-to-reel production) or layers can be sequentially built up where electroplating is not a viable option. Inkjet printing is well suited for low-viscosity, soluble materials like organic semiconductors. With high-viscosity materials, like organic dielectrics, and dispersed particles, like inorganic metal inks, difficulties due to nozzle clogging occur. Suitable inks are usually based on acqueos colloidal dispersions of conductive nano-particles. Ink jet printing for electronics is currently dominated by silver based inks, even if good advancements have been reached in the formulation of copper based, nickel based, aluminium based, and silicon based inks. A technology very similar to inkjet printing, but slightly more complex is the Maskless Mesoscale Material Deposition technology (M3D), which is a sort of aerosol printing able to deposit raw materials like metals, insulators, ceramics, polymers or biological materials on a variety of substrate materials such as plastics, metals, ceramics, glass or silicon (this is possible as long as the particle size of the raw ink materials does not exceed a size of 500 μm). With this printing method, feature sizes down to 10 μm have been realized.

On the other hand, screen printing, also known as silkscreen or serigraphy, is a printing method which makes use of a screen. A screen is made of a piece of porous, finely woven fabric (called mesh) which is stretched over a frame. Certain areas of the screen are blocked with a non-permeable material to form a stencil, which is the negative of the layout to be printed. A suitable transfer ink which can be pressed through the mesh is applied and a roller or squeegee is moved across the screen stencil, forcing or pumping ink past the uncovered areas of the screen, and depositing it on the final circuit substrate. Screen printing is able to produce thick layers from paste-like materials. This method can produce conducting lines from inorganic materials, but also insulating and passivating layers, whereby layer thickness is more important than high resolution. Its 50 m^2/h throughput and 100 μm resolution are similar to inkjets. This versatile and comparatively simple method is used mainly for conductive and dielectric layers, but also organic semiconductors (e.g. for OPVCs and OFETs).

Nowadays, it is well common to hear about TFP (or PTF or Thick Film Technology). Thick film technology is simply another name for the technique of applying a layer of material onto a substrate via screen printing. Thick film layers are prepared starting from powders. The basic layer material is mixed with polymer and glass binders: these binders are needed to give the final product both strength and adhesion to the substrate, moreover they act upon temperature dependant electric properties). A heavy organic solvent is also added to form an ink of suitable viscosity. The ink is then screen printed, dried to remove most of the organic medium (100°C-200°C) and fired (450°C-900°C) to form a continuous layer with specific electrical behavior and tolerances.

Nowadays, screen printing is not the major technology for pattern generation in printed circuit manufacturing: this is because of its lower resolution compared to the photolithography/etching process. However, advanced screen-printing processes have recently been developed and they have an equivalent pattern resolution with more advantages with respect to conventional photo-etching methodologies. The major advantage of the screen printing is that material formation and patterning can be processed in only two steps, while they need several steps to be built via photolithography/etching methods, with the need of additional processing materials such as photo resist and etching solutions. Figure 2.3 summarizes the different PCB creation processes for the two aforementioned methodologies.

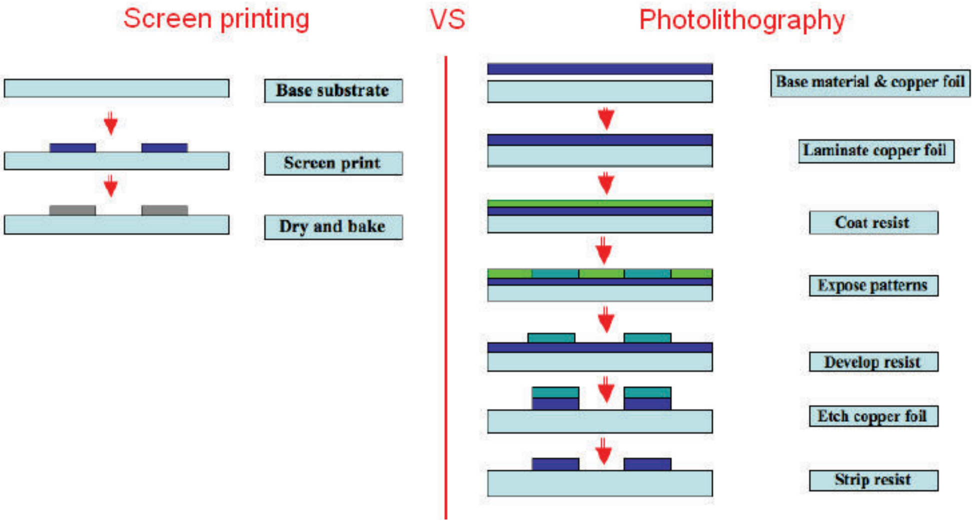

Figure 2.3: Comparison between screen printing and photolithography processes [75].

As an example of actual applications, a layer containing Ag/Pd, Ni/Cr, Mo or C powders printed in the form of a resistive track onto an insulating substrate is nothing but a heating element.

As mentioned before, the ink composition governs the behavior of the thick film layer; therefore, by changing the powder composition, it is possible to print dielectric or conducting areas, as well as resistors. Furthermore, properly selecting the binder material and processing conditions, it is possible to apply several thick film layers onto many different substrates.

As an example, the base film can be polyimide or polyethylenenaphthalate; conductive traces can be built with silver paste or aluminium paste. Four-point conductivity measurements show that the sheet resistance[2] of a screen-printed aluminium conductor is 60 mOhm/sq when pure aluminium is used. The typical sheet resistance for screen-printed microparticle silver pastes is about 20-50 mOhm/sq. If the aluminium ink is doped with magnesium, the sheet resistance increases to 120 mOhm/sq. Resistors can be obtained from carbon paste; insulation layers can be made of epoxy resin ink, polyester resin ink or polyimide resin ink (possibly doped with barium titanate powder).

The screen-printing process is capable of building several layers with a simply additive mechanism, including insulation materials, resistance materials, dielectric materials for capacitance and more.

Screen-printing technology is also capable to generate via holes between the conductive layers without drilling and copper plating; therefore it provides the

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[2] The conductivity or resistance values of inks are normally given in Ohm/square/25μm.

opportunity to produce low cost solutions for embedded passives in multi-layer circuits. An optimized combination of the process conditions and materials is capable of generating 30μm line/space pitch on thin flexible substrates. Supplemental processes can generate 80μm via holes for double sided and multi-layer circuits. To be precise, printing machines and screen masks are already capable to screen-print 10 to 20μm line and space. Research is underway to develop production quantities of conductive paste materials to exploit this possibility and realize ultra fine conductors. At the present time, there is no difficulty in building multilayer architectures of up to 10 conductor layers by simply repeating the screen-printing processes alternating conductive and insulating pastes. If necessary, a coating treatment is used prior to the screen-printing processes to enhance the bond strength between the layers. The PCB can be equipped with silver based and solderable terminations or pads, suitable for soldering or mechanical contact, so that SMDs can be built onto the same substrate.

The possibility of implementing RTR processing adds value to this printing process by achieving low cost manufacturing.

Up to now, screen printing technology can produce conductive traces and planes, dielectric layers, passive elements (resistors, capacitors, inductors), antennas, OLEDs, memristors, TFTs, photovoltaic cells…

A certain number of tricky aspects are connected with the use of conductive inks or pastes. The first is that there is large disparity between the sheet resistivity stated by manufacturers and the sheet resistivity actually measured in the lab. However, the issue is resolved in standard practice through designing the resistors for larger values than is desired prior to any tuning (e.g. laser trimming). Another aspect to be kept under control is the variation of resistance with temperature, in particular when printed resistors require an exact value with tight tolerance (such as in a timing circuit). A third area of concern is dimensional stability, since the PTF curing process makes the volatiles evaporate from the printed parts, and those components begin to shrink (for example, a resistor will loose as much as 50% of its original print thickness due to this procedure). This shrinkage can pull at the flexible substrate, thus warping it slightly.

Table 2.5: Overview of TFP pastes [70].

Conductor pastes
The most commonly used conductive filler is silver, and there are a number of pure silver inks available on the market. A typical PTF silver ink conductor has a resistivity of approximately 15 mOhm/sq/mil, or approximately an order of magnitude less than silver wire. The reason is attributed to the fact that the silver particles which make up the conductor pastes are often coated with oxides, surface agents, and binders, all of which have the effect of increasing the electrical resistance. One of the problems with pure silver inks is electromigration. In standard ceramic thick films, this problem is greatly reduced through the addition of palladium into the silver paste. In PTFs, suitable silver mixtures have not been developed by the industry, and therefore, the issue is solved by overprinting. After the silver ink has dried and cured, a layer of carbon ink is printed over the silver traces (as oversized traces so as to completely cover the silver), including the edges. This process significantly retards the phenomena of silver electromigration. The problem still persists however, for single-sided multilayer applications, in which multiple conductor layers are separated by dielectric layers. Over extended periods of time, reliability issues become a concern as the silver can sometimes migrate through the printed dielectric layers. A second problem with silver inks is the characteristic of silver leaching or dissolving into lead-tin solder.
A popular alternative to silver ink is copper ink. The challenge with utilizing copper inks is inhibiting copper's tendency to oxidize under heat and humidity conditions. A number of conductor inks utilize copper flakes that have been bonded with nitrogen bases to form stable copper complexes that prevent oxidation. The most prevalent copper based PTF solution, however, is to use copper flakes plated with silver. During soldering, the silver is leached into the solder to expose the unoxidized copper. A third alternative, but as of yet unsuccessful, are the intrinsically conductive polymers (ICPs). ICPs would make molded polymer circuits possible, fine wires which could be spun like polymer fibers, and offer ultrafine line circuitry. The problem with ICPs is that they lack ease of processability and chemical stability. Processes are typically tedious and difficult, the materials are inflexible, and they often exhibit instability in open atmosphere. The majority of ICPs oxidize and lose conductivity under ambient conditions, a degradation which is accelerated under high temperatures and humidity.

Table 2.5: Overview of TFP pastes [70].

Resistor pastes
Considerable efforts over the past decades have been invested into the development of PTF carbon based resistor inks, which are typically offered with sheet resistivities of 10 Ohm, 100 Ohm, 1 kOhm, 10 kOhm, 100 kOhm, 1 MOhm, and 10 MOhm. There are more stringent demands placed on the resistor pastes due to the requirement that the inks' resistive values must be predictable, uniform, and consistent over time and operation. Temperature coefficient of resistance (TCR) is an important characteristic since the resistor must be stable over a reasonable temperature range. Thermosets form the most stable resistors and products with the best endurance and reliability characteristics. Thermoset resins undergo a chemical change when processed, which gives this resistor material a high chemical flexibility when deciding hardness, cross-link density, and rate of cure. Thermoplastic resistors form the other major category, although sensitive to solvents and less robust with regards to time and temperature, they are easier to formulate and process. In addition, the thermoset resistors require curing at higher temperatures, approximately 150÷200 °C, which result in these resistors being less flexible and may prove as a problem when utilized with low temperature polymer substrates. There has been some experimentation with other resistor pastes which utilize room temperature air drying or ultraviolet (UV) curing, instead of the traditional thermal and infrared curing.
Dielectric pastes
The majority of dielectric inks are UV or thermal cured, and are used as protective coatings over the conductor and resistor prints. Polymer dielectric inks possess very low dielectric constants, typically ranging from approximately 2.5 to 6, thus limiting their effective range to manufacture capacitors. Ceramic fillers can be added to the pastes to increase the dielectric constant value, but the application of power converters mandates the production of capacitance values much higher than these figures.

Published studies [70] investigate the viability of printing PTF resistors to etched copper metallized surfaces as an alternative. This capability would provide an engineer with the option of integrating low profile inexpensive resistors into their designs without sacrificing the efficiency of pure conductor traces. Copper metallization shall be nickel plated prior to the PTF resistor printing in order to reduce bad prints and contacts. The work demonstrates that it is feasible and viable to print PTF resistors on copper metallization traces. However, the main concern is that overly thick metallization conductors (on the order of more than 1 or 2 mil) may cause opens in the printed PTF resistors.

A very interesting feature is that the screen printing method allows to build in a simple additive way a certain number of passive circuit elements. To build functional electronic circuits on a thin film the advanced screen-printing process has to be repeated up to ten times, with exact dimensional control and alignment. Nonetheless, interesting results can be obtained.

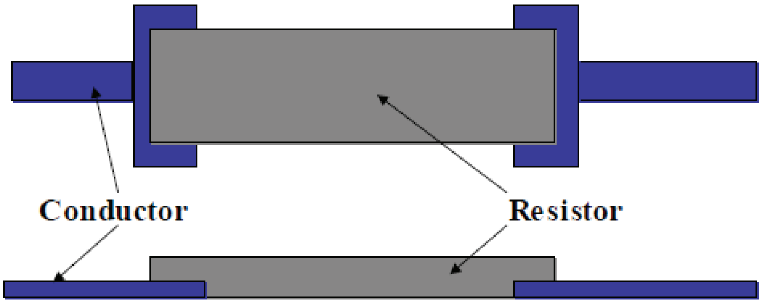

Figure 2.4: Printed resistor [76].

The printed resistor (Figure 2.4) is the simplest component, and, besides being useful in electronic circuits, it can also be a heating or sensing device.

The capacitance elements require three steps of screen-printing on the conductor layer. The capacitance materials with high dielectric constants are screen printed between the two electrodes as shown in Figure 2.5. It is much simpler compared to the etching process with high dielectric constant laminates.

Just to offer an example of the electrical performances of the printed capacitors with high dielectric constant materials on flexible substrates: a 2 mm square printed capacitor can generate 200 pico Farads capacitance at 1 kHz frequency. The same construction generates 2 nano Farads in a 5 mm square space. It is foreseen that the combinations of thinner dielectric and multi-layer construction will make the available capacitance ten times larger in the same footprint.

There are two ways to build printed inductors, as shown in 2.6 a) and b). The first construction method uses drilled via holes through the base substrate film. The second construction method uses printed via holes on base substrate film. Multiple printed coils are formed on a thin film (e.g. polyimide) with via hole connections (punched or printed) in order to create the passive element in a small space. The

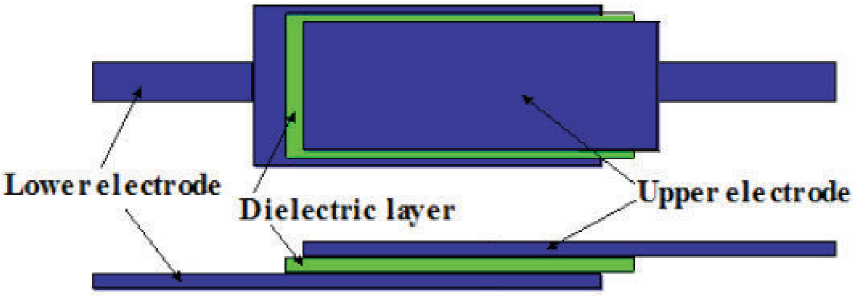

Figure 2.5: Printed capacitor [76].

same processes can be repeated to generate higher inductances.

At the time being, many electronic components can already be built in thin bendable form, paving the way to fully flexible electronic circuits. However, before a completely flex device can be built, there are a few issues to be solved: in particular, a small number of basic circuit elements are still missing. The memristor is one of those. The memristor (portmanteau of memory resistor) is a passive two-terminal electrical component in which there is a functional relationship between electric charge and magnetic flux linkage. When current flows in one direction through the device, the electrical resistance increases; and when current flows in the opposite direction, the resistance decreases. When the current is stopped, the component retains the last resistance that it had, and when the flow of charge starts again, the resistance of the circuit will be what it was when it was last active. Switching memristor devices are being developed for application in nanoelectronic memories.

A recent study has demonstrated the feasibility of rewritable low-power operation non-volatile physically flexible memristor devices. These devices are made of TiO2 deposited in sol gel form on a commercially available polymer sheet. The fabrication process is possible at room temperature and is inexpensive. The final device exhibits memory behavior consistent with a memristor, demonstrates an on/off ratio greater than 10000 : 1, is non-volatile for over $1.2 \cdot 10^6$ s, requires less than 10 V, and is still operational after being physically flexed more than 4000 times.

Even if these components are still in a prototypical stage, they are a promising candidate for flexible memory devices. This is an encouraging step for the realization of fully flexible electronics. A lot of research is ongoing [77]. In October 2011, HP laboratories announced the commercial availability of memristor technology within 18 months, as a replacement for Flash, SSD, DRAM and SRAM, and in the same period PARC/Xerox announced the successful creation of printed memristive junctions.

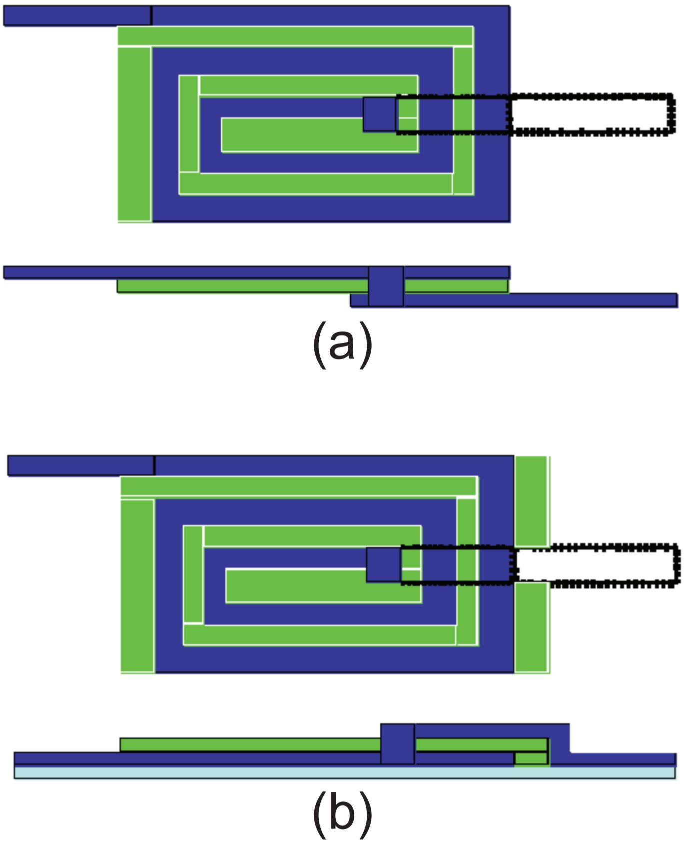

Figure 2.6: Printed inductors, two construction methods [76].

2.1.3 System in Foil and Ultra Thin Chips

System-In-Foil technology is the name of the newborn idea of applying electronics on thin substrates, such as foils, with the aim of obtaining a flexible final product. The first solution that comes to mind when thinking of systems-in-foil is to build flexible polymeric integrated circuits instead of rigid silicon ICs. Unfortunately, even though fully functional polymer ICs have been demonstrated, the mobility of charge carriers in polymers is not yet comparable to silicon. Many applications still require the integration of standard silicon (electronic) or glass (opto-electronic) technology without any alternative. Therefore there still is the problem of handling rigid integrated circuits. Of course, classical ICs are rigid, but by using them in the naked die form and by thinning them down to 25 μm or less, they become slightly flexible (typically 1 cm bending radius for 25 μm thick chips).

Consequently, one of many crucial aspects in developing ultra thin flexible packages is die thickness. The reduction of the chip thickness can be achieved with the thinning of the whole wafer at the back (after completion of device processing on the front side).

There are four primary thinning techniques: mechanical grinding, chemical mechanical polishing (CMP), wet etching, and atmospheric downstream plasma (ADP) dry chemical etching (DCE).

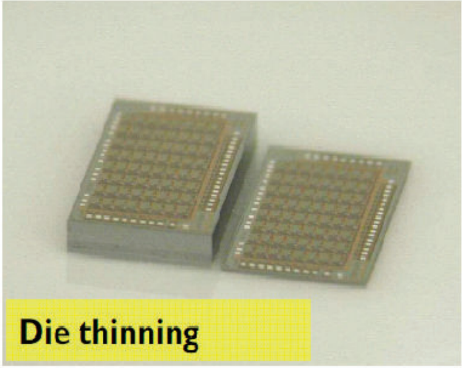

Figure 2.7: Wafer thinning example [78].

Wafer level thin film technology attracts interest because it has multi-layer, three-dimensional wiring options, potential integration of passive components and mechanical flexibility for optional folding operations. Up to now, ICs built with wafer thinning technology have reached thicknesses in the order of 1 mil $\div$ 20 μm keeping at the same time good mechanical strength and high reliability during temperature shock and cycling.

Thin chips, coupled with a flexible carrier, enable the manufacturing of flexible systems-in-foil, and also offer the opportunity for a manufacturer to create very flat and lightweight systems (if the silicon chip is embedded inside a polymeric film, the overall thickness of the system can be less than 100 μm).

Since this thin wafer technology is commercially available, upon it IMEC (R&D lab for nanoelectronics headquartered in Leuven, Belgium) and CMST (Centre for Micro Systems Technology, IMEC associated labs at Ghent University) developed a technology for embedding ultra thin dies in flexible substrates.

This novel packaging concept is named Ultra Thin Chip Package (UTCP) and has been studied under EC Projects FP6-IP-SHIFT (Smart High-Integration Flex Technologies) and FP7-STRP-TIPS (Thin Interconnected Package Stacks).

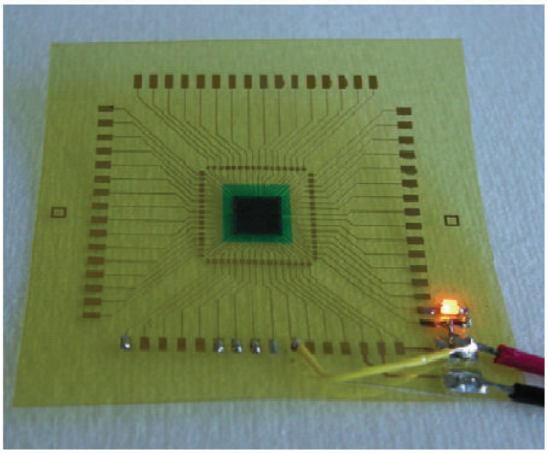

Figure 2.8: UTCP package of a MSP430F149 microcontroller thinned down to 25 μm [78].

UTCP is based on the concept of embedding ultra thin chips, with thicknesses below 30 μm and footprint areas in the order of 100 mm^2, in between two flexible layers, resulting in a chip package with a total thickness of only 50÷60μm. This package can then be assembled on PCBs or FPCBs, replacing naked dies..

The final device is so thin that the whole package is bendable. It can be embedded in standard flex circuits with standard lamination, through-hole drilling and metallization techniques. Moreover, it paves the way for die stacking. Die stacking saves space, providing large benefits in electrical density and weight and may also result in an enhanced electrical performance, as a result of the shorter interconnections between circuits.

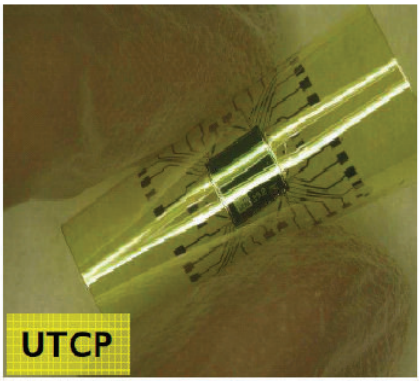

Figure 2.9: UTCP resulting device is flexible [78].

IMEC-CMST process is described as follows. The base substrate is a uniform polyimide layer, applied (spin coated and cured) on a rigid carrier. Then BCB is dispensed to serve as adhesive layer for fixation of the off-the-shelf dice. After placement of the ultra thin chip, the BCB is cured. Next, the second spin-on polyimide layer is applied and cured. Vias to the contacts of the chip are laser drilled and the contact metal layer is sputtered and photolithographically patterned. This metal layer provides a fan out to the contacts of the chips (a fan-out metallization makes the alignment less critical, so that chips with finer pitches can be used, and provides an handy electrical interface, so that the die can be tested before embedding). Finally the whole package is released from the rigid substrate.

Activities for transfer from lab to fab, and for cost reduction are underway.

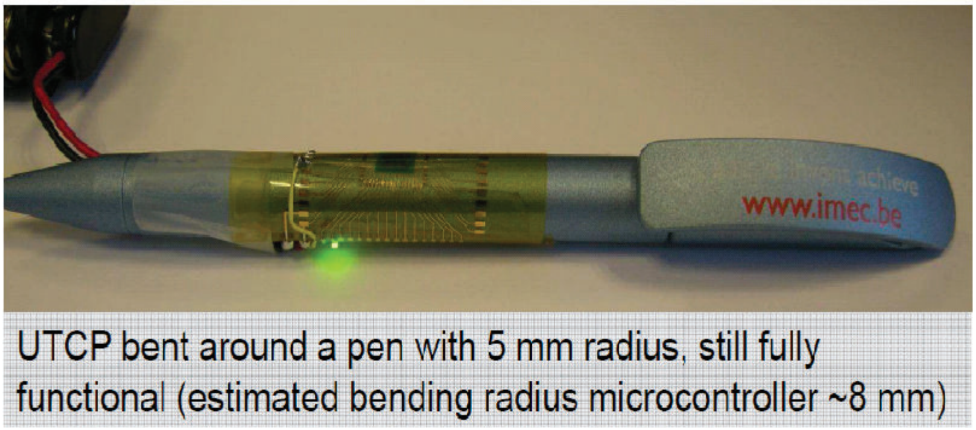

Figure 2.10: Functionality of UTCP demonstrated after integration [78].

2.1.4 Stablcor

Stablcor, patented and produced by Stablcor Technology Inc., is a thermal management technology for the Printed Circuit Board and Substrate markets. It is a laminate thermally and electrically conductive carbon composite material. It has four main benefits with respect to standard PCB substrates:

- Thermal Conductivity: it is well suited for electronics thermal control, since it allows efficient conduction cooling and reduction of hot spots on the PCB.
- CTE: it allows tailoring the PCB CTE to match with ceramic or flip chip type packages, it reduces CTE mismatches and increases Solder Joint Reliability (SJR).
- Stiffness: it allows eliminating metal reinforcement and stiffeners, it increases rigidity without adding weight, thus increasing shock and vibration reliability.
- Density: it is as light weight as typical glass fiber composite material (density 1.75 g/cc).

Stablcor technology is ideal for conduction cooling, because it has quite a high in-plane thermal conductivity. Thus, it acts as a built-in heat spreader and moves heat away from a hot spot quickly to the colder area of the PCB. Also, since it is usually located very close to the surfaces of the PCB, there is a very short thermal path from the heat source to the Stablcor layer, which then enables heat to move to the nearest heat sink.

Table 2.6: Different types of Stablcor: EP387 are epoxy based, LC909 are polyimide based.

Product Name	**Core Thickness (in)(μm)**	**Copper Thickness (oz)**
ST10-EP387	0.0045 in (114μm) 0.006 in (152μm) 0.009 in (229μm) 0.018 in (457μm)	H/H, 1/1
ST10-LC909	0.009 in (229μm)	H/H, 1/1
ST325-EP387	0.008 in (203μm)	H/H, 1/1

With Stablcor it is possible to tailor the in-plane CTE of a PCB by selecting the right type, thickness, and location of the layers within the PCB stack-up. With this approach it is quite easy to obtain a CTE = 8-10 ppm/°C to closely match with CBGA, or a CTE 2-4 ppm/°C to match with flip chips (the lowest in-plane CTE in a finished PCB is $\sim$3.0 ppm/°C). Moreover, Stablcor material does not have a high through-plane CTE as other heat spreading technologies have (i.e. Thermount). Through-plane CTE of Stablcor is only 45-55 ppm/°C[3].

Stablcor increases rigidity without adding weight to the PCB, because carbon fiber has a very high tensile modulus combined with a very low density. The best rigidity can be achieved by using at least two layers of Stablcor material, located as far as possible from the neutral axis (center line) of the PCB stack-up. By using proper material ratio it is possible to reduce or eliminate heavy metal stiffeners.

Therefore, Stablcor allows a PCB to:

- Operate cooler: the PCB has reduced hot spots, behaves as a heat sink, and reduces thermal stress on components.
- Match CTE: a PCB with tailored and controlled coefficient of thermal expansion can accommodate ceramic and flip chip packages more reliably.
- Be stiffer: a stiffer PCB prevents warpage and increases yields for component placement.

At the present time, there are two types of Stablcor laminate materials, ST10 and ST325. Their properties are summarized in Tables 2.6 and 2.7. They can be based on epoxy or polyimide resins. EP387 (epoxy) has Tg=170 °C and LC909 (polyimide) has Tg=240 °C. The most common laminate has copper on both sides: half ounce (0.7 mil = 17.5μm) and one ounce (1.4 mil = 35μm) copper are typical thicknesses. Such a laminate can be bonded with the rest of the layers using standard off-the-shelf prepreg, like 2 ply of 106 prepreg or equivalent.

The material is tested and rated to flammability V-0.

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[3] Just to compare, Thermount material has CTE$_z$ = 110-120 ppm/°C, standard epoxy and polyimide material have CTE$_z$ = 50-60 ppm/°C.

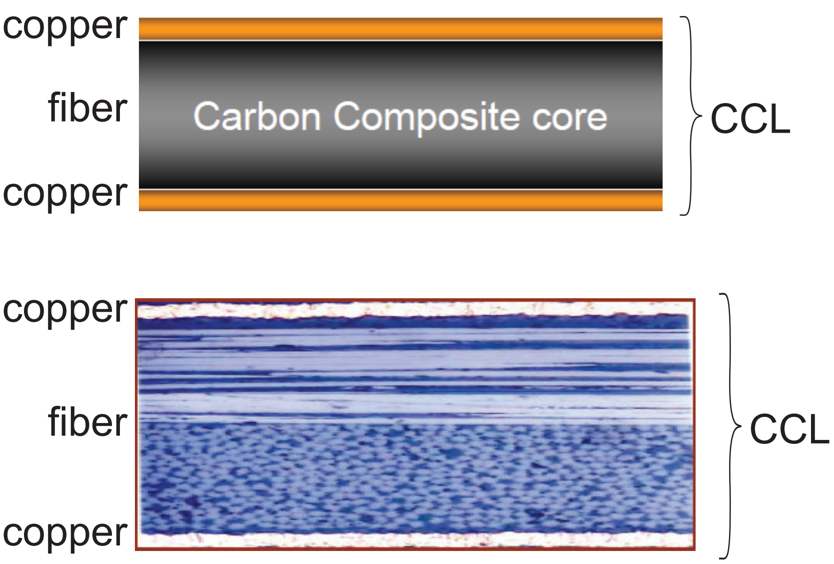

Figure 2.11: Stablcor Carbon Core Laminate, sketch and photo (property of Stablcor Technologies Inc.).

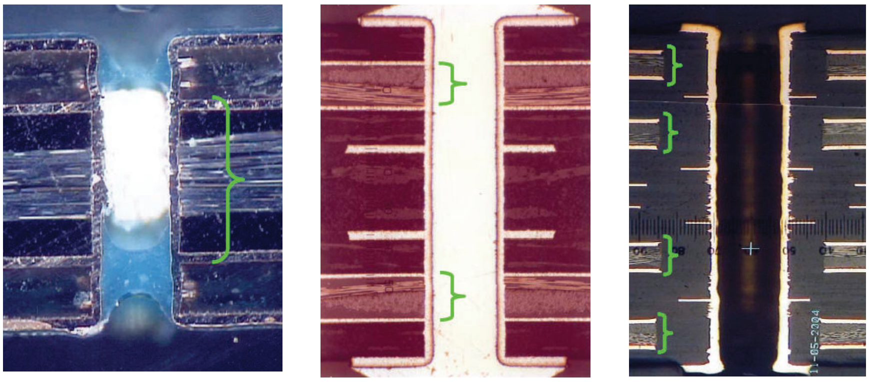

Figure 2.12: Stablcor Carbon Core Laminate highlighted in PCB stacks. From left to right: 3-layers 1-core board, 2-layers 2-cores board, and 12-layers 4-cores board (property of Stablcor Technologies Inc.).

Table 2.7: Comparison of Stablcor (in-plane) properties with other PCB industry materials.

	Thermal Conductivity (W/m/K)	**CTE (ppm/°C)**	**Tensile Modulus (Msi)**	**Density (g/cc)**
FR-4/E-glass	0.3 - 0.4	16 - 20	3.5 - 4.5	1.6 -1.8
Polyimide/E-glass	0.2 - 0.4	15 - 19	3.5 - 4.5	1.5 -1.7
Copper	385	17 - 20	12	8.92
Copper-Invar-Copper (CIC)	108	5 - 6	19	9.90
Stablcor Laminate unclad	ST10: 3	ST10: 4.5 - 6	ST10: 9	1.6 - 1.65
	ST325: 97	ST325: 1 - 3	ST325: 34	
Stablcor Laminate with l oz Cu clad	ST10: 75	ST10: 5 - 7	ST10: 8	2.91 - 2.99
	ST325: 190	ST325: 2 - 4	ST325: 28	

Usually the whole Stablcor laminate (Cu - Stablcor composite - Cu) is used as a single plane layer (preferably a ground plane layer[4]) in the PCB stack-up. If Stablcor material is used as a plane layer, it does not affect impedance values as long as there is proper dielectric material between the signal layer and the Stablcor layer. No signal layer can be built with Stablcor.

To take advantage of the benefits brought by this technology, only a selected number of plane layers need to be replaced with Stablcor, typically the choice is on the 2nd layers from the outer ones. This two-layers (next to the surface) configuration is the most common design structure. The rest of the PCB can be built with standard FR4 or polyimide materials: EP387 grade Stablcor is used with FR4 dielectric, while LC909 grade is used with polyimide dielectric. In the latter case, it is highly recommended to use low cure temperature (<400 °F) polyimide prepregs.

Stablcor is compatible with blind buried via technology designs, as long as its layers are symmetrical into each sub-assembly and final lamination stack-up. It is also compatible with laser drilling process.

Published studies [65] explored the mechanical behavior of Stablcor-based PCBs. Several 16 in long by 1.25 in wide by 0.062 in thick PCBs were fabricated, and bonded together with an adhesive to form box beams. The box beam specimens underwent three point bending flexural testing, and cantilever mode flexural testing. An analogous aluminium box beam was also tested as a reference.

The Carbon Core Laminate (CCL) box beam structures exhibited deflection under load followed by catastrophic failure by cracking at the point of ram contact. Cracking was observed on all sides of the beam. There was minimal separation along the adhesive bond lines. As a result, the test campaign showed that the strength to weight ratio increases when an increasing number of carbon fiber based layers are added to the PCB stack (from 0 to 3 layers, while 4 layers led to increased thickness and weight and therefore reduced specific performance).

As mentioned before, the ST-10 and ST-325 materials have different heat transfer properties. The ST-10 CCL weave conducts heat at 75 W/m/K, and the ST-325 carbon core weave conducts at 175 W/m/K.

In another study [66], CCL layers were incorporated near the top and bottom of dummy printed circuit boards panel to form a sandwich construction and evaluate its thermal performance. There were three different types of printed circuit boards tested. They were identical in size, length, width, and thickness: a Compact PCI Bus standard card size of 233.35 mm by 160 mm by 2 mm. The first type was of standard polyimide and copper inner layer construction with no CCL. The second type included two layers of ST-10 CCL placed symmetrically within the board cross-section. The third type included two layers of ST-325 CCL placed

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[4] It is possible to use Stablcor laminate as a power layer, but it is not recommended, because there is a risk of having Stablcor material exposed along the edges of the printed circuit board. In case, care must be taken to protect the edges from a potential short circuit, and this usually requires additional processing steps, which also leads to low yield and increased cost. Stablcor material can be used as a split plane: it can not create an island within a plane area, but it can be used as a peninsula type, or as long as both ends of the split plane line comes to the edges of the PCB. However, since it has to spread to the edges, it brings the same drawbacks listed for power planes.

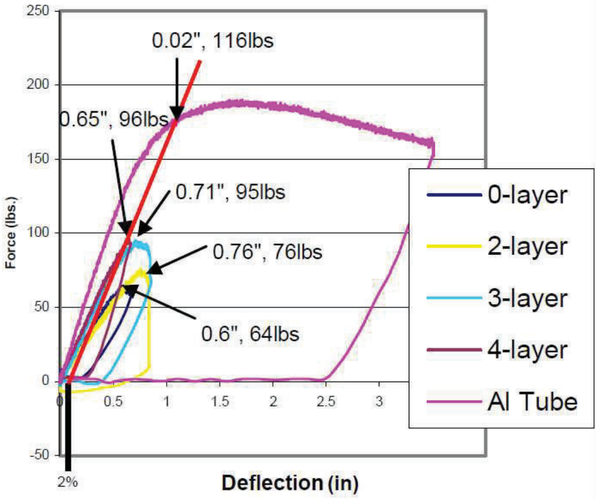

Figure 2.13: Cantilever test of carbon core box beam versus aluminium beam box.

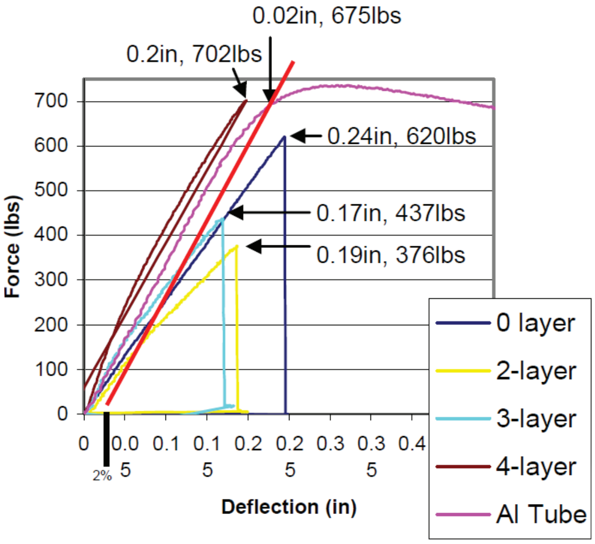

Figure 2.14: Three points test of carbon core box beam versus aluminium beam box.

symmetrically within the board construction. The test boards were placed in a vacuum chamber and heated with on-board resistors (approximately 5 W each). Infrared imaging was utilized to take an image of the board at zero time and once every minute for 30 minutes. Results show that the ST-325 construction provided a more efficient heat path through the board as indicated by lower temperatures at the resistor heat source (locations SP01, SP02 and SP03 in Figures 2.15, 2.17, 2.19) and higher temperatures further away from the heat-generating resistors. On the other hand, due to a copper layer removed from the top and bottom portion of the cross-sectional stack-up[5], the ST-10 test vehicle had reduced thermal properties.

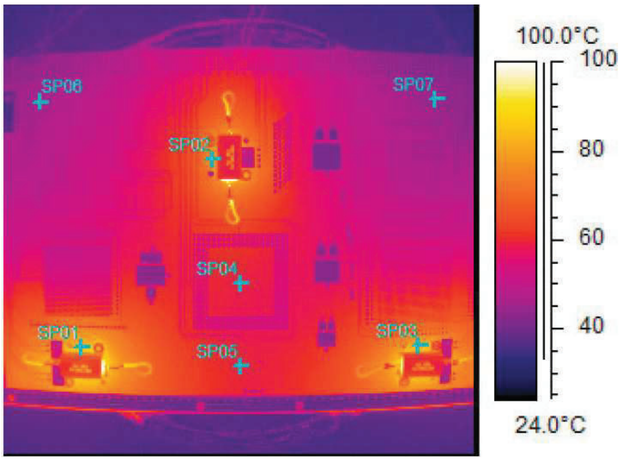

Figure 2.15: Thermocamera reading for traditional Cu/PI.

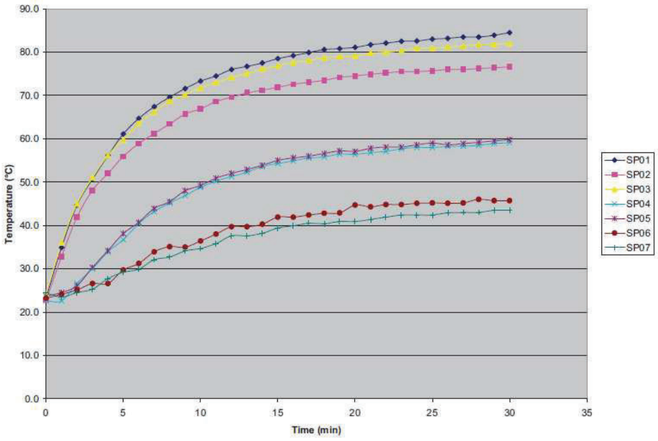

Figure 2.16: Temperature reading for traditional Cu/PI.

2.1.5 Carbon-Carbon

In conventional composites, polymeric matrix strongly affects the overall thermal conductivity of the material. In fact, even if composite's fibers have extraordinarily

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[5] The intent was to optimize the design, so it could also be used for the solder interconnection reliability test. The copper was removed in order to obtain a more desirable thermal coefficient of expansion property to help reduce solder joint stresses.

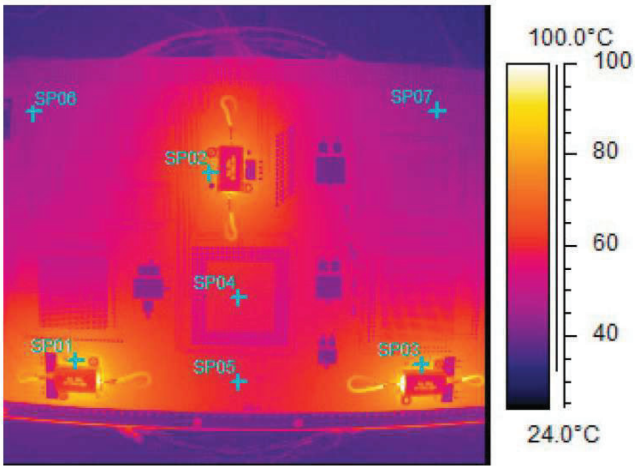

Figure 2.17: Thermocamera reading for Stablcor ST10.

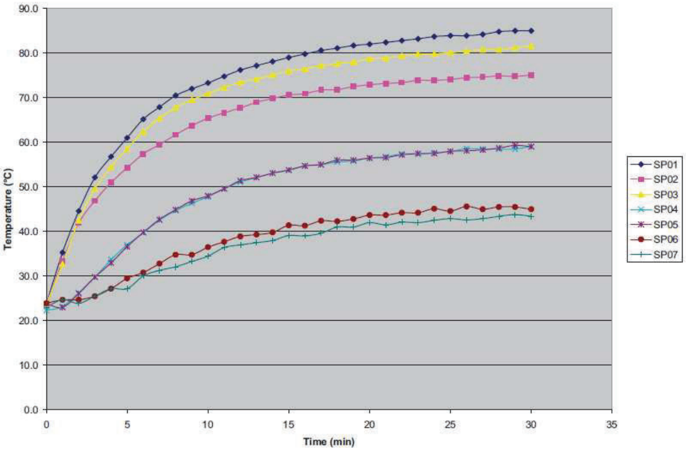

Figure 2.18: Temperature reading for Stablcor ST10.

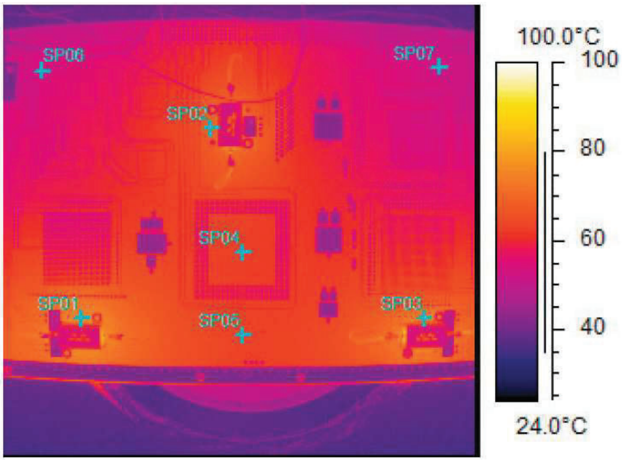

Figure 2.19: Thermocamera reading for Stablcor ST325.

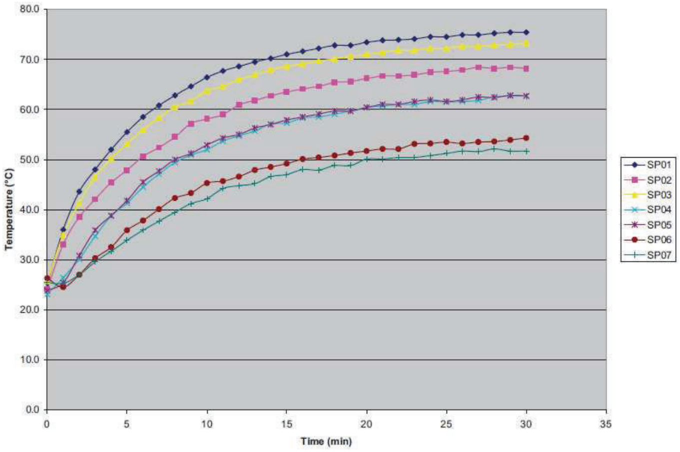

Figure 2.20: Temperature reading for Stablcor ST325.

high K values, the presence of a matrix with a limited conductivity is responsible for a remarkable reduction of global thermal performances.

Therefore, the logical consequence is the adoption of a different matrix, more precisely made of carbon graphite. Such composites, in which carbon fibers are coupled with graphitic binder, are commonly known as Carbon-Carbon (C/C). Up to now, they have been used in high temperature insulations and heat shields. Common applications are exit cones of high performance solid rocket fuel nozzles, aircraft brakes, oxidation resistant coatings…

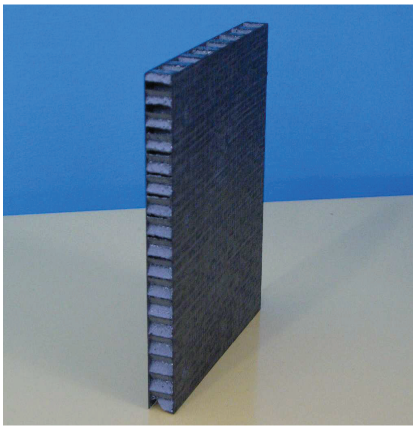

Figure 2.21: Panel made of Carbon-Carbon skins bonded to Carbon-Carbon core with high face-to-face conductivity.

In the last decades, patents have been filed with the description of the process to obtain Carbon-Carbon honeycomb and to bond it to Carbon-Carbon skins in order to create high-conductivity panels[6].

Up to 2009, the only available producer of such materials was Ultracor, Inc. (U.S.A.). This small firm produces "off-the-shelf" panels at affordable cost. Their sandwich panels are constructed from a low density, low modulus, Carbon/Epoxy honeycomb and thin low modulus Carbon/Epoxy facesheets. The entire structure

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[6] They are manufactured through carbonization and high-T treatment of conventional CFRP.

is then processed into a high thermal conductivity, high modulus structure that has exceptionally good through the thickness thermal conductivity, low CTE ($-0.15\ °C^{-1}$), and low density. The process to obtain a whole C/C sandwich panel includes the following steps:

- Manufacturing of CFRP facings and honeycomb core.
- Carbonization and densification (CVI) of facings and core separately.
- Adhesive bonding of facings and core.
- Carbonization of assembled sandwich panel.
- Graphitization at high temperature (>2800 °C).

In particular, even if they come from low-cost pitch precursors, these materials and the typical cell dimensions allow high conductivity even in the "through-the-plane" (z) direction, with little or no impact on structural mass. For example, Ultracor® panels have skins with nominal $K_{xy} = 300\ W/m/K$ (as opposed to $K_{xy} = 170\ W/m/K$ typical for aluminium) and sandwich nominal skin-to-skin $K_z = 40 \div 60\ W/m/K$ (as opposed to $K_z = 2\ W/m/K$ typical of Al-Al panels). C/C honeycomb density is circa 70 Kg/m^3, while typical aluminium honeycomb has a density of 50 Kg/m^3.

The fibers used by Ultracor to get the Carbon/Carbon panels are usually Nippon Graphite SFYS-15 or Amoco P30x in woven configuration.

Thales Alenia Space Italy bought from Ultracor some Carbon-Carbon sandwich panels having the following nominal characteristics:

- Honeycomb core was made of fabric type SFYH-15 Z and resin system RS-11 (fiber YS-15; prepreg 105 g/m^2). Cell size was 1/4 in (6.35 mm), thickness was 20 mm and density was 4.5 $pcf \simeq 72.1\ kg/m^3$. Honeycomb core was of spliced type.
- Skins were made of quasi-isotropic laminates. Each skin was made with 8 plies of fabric and resin system RS-11 (fiber XN-25; prepreg 53 g/m^2). Thickness was 0.6 mm.

The total thickness of each sandwich panel was 21.5 mm.

Additional samples were also acquired, in order to perform characterization tests on the material's mechanical, thermal and electromagnetic performances. The samples consisted of one Carbon-Carbon honeycomb core of $150 \times 150\ mm$, 20 mm thick, and one Carbon-Carbon laminate of $150 \times 150\ mm$, 0.8 mm thick. Both the core and the laminate were produced and processed as the full panels, but they were not bonded together.

Under a mechanical point of view, data declared by the manufactured are listed in Tables 2.8 and 2.9.

The mechanical properties of honeycomb core in C/C were determined using ASTM C365 and C273 respectively for core compression and core shear. Table 2.8 shows two types of C/C honeycomb and their mechanical properties. Table 2.9 shows the mechanical properties obtained by testing a core of 0.5 in.

Table 2.8: Ultracor Carbon-Carbon mechanical properties compared with other materials.

Type	Density	Flatwise tension	Comp. strength	"L" Shear strength	"L" Shear modulus
	pcf (g/cc)	psi (KPa)	psi (KPa)	psi (KPa)	ksi (MPa)
PCC-300-3/8-4.0	4 (0.064)	98 (676)	500 (3447)	325 (2241)	194 (1331)
UCC-2158-3/16-10	12 (0.192)	-	1411 (9729)	1025 (7067)	265 (1827)

Table 2.9: Ultracor products mechanical properties.

Product Code	Density pcf	Materials	Compressive (ASTM C365)		Plate Shear (ASTM C273)			
					L-Direction		W-Direction	
			Strength	Modulus	Strength	Modulus	Strength	Modulus
			psi (MPa)	ksi (MPa)	psi (MPa)	ksi (MPa)	psi (MPa)	ksi (MPa)
3/8 - 5052 - .0015	2.3	Aluminum Hexcel	200	45	135	32	80	16.2
UCC-3173-3/8-2.0	2	±45°Pitch	140 (0.97)	28 (193)	148 (1.02)	53 (365)	-	-
3/8 - 5052 - .001	1.6	Aluminum Hexcel	95	20	85	21	50	11
UCC-2158-3/16-10	10	±45°PAN	1393 (9.6)	157 (1082)	1025 (7.07)	225 (1551)	610 (4.21)	103 (710)
3/16 - 5052 - .003	8.1	Aluminum Hexcel	1720	350	725	135	480	54

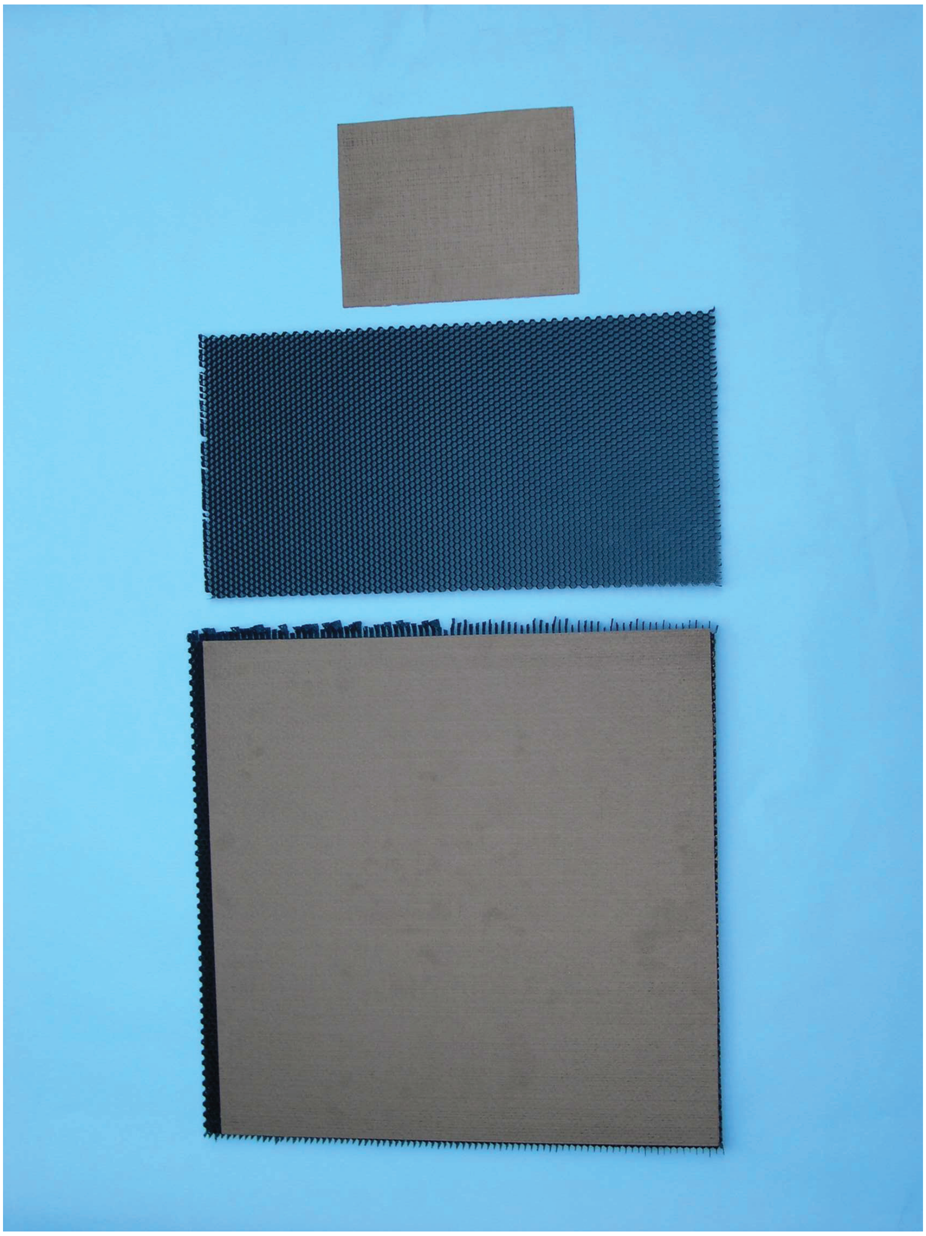

Figure 2.22: Carbon-Carbon skin and honeycomb produced by Ultracor.

Table 2.10: ABB C/C panel: facing tensile properties.

	Strength, σ_{tu} (MPa) Average ± std dev	**Elastic modulus, E (GPa) Average ± std dev**	**Elongation, ε_u (%) Average ± std dev**	**Failure mode**
Transverse	61 ± 9	37 ± 2	0.18 ± 0.05	30% of specimens: LGM 70% of specimens: LAT
Longitudinal	61 ± 14	39 ± 5	0.16 ± 0.04	

Table 2.11: ABB C/C panel: sandwich three-point bending test results.

Specimen	**Core shear ultimate strength τ_{ult} (MPa)**	**Facing stress σ_{sf} (MPa)**	**Bending stiffness D (N mm^2)**	**Shear stiffness U (N)**	**Failure mode**
SBF01	0.45	41	$0.31 \cdot 10^9$	$1.2 \cdot 10^6$	Core-facing bond
SBF02	0.34	31	$0.31 \cdot 10^9$	$1.2 \cdot 10^6$	Core-facing bond
Average	0.40	36	$0.31 \cdot 10^9$	$1.2 \cdot 10^6$	

Table 2.12: ABB C/C panel: sandwich four-point bending test results.

Specimen	**Core shear ultimate strength τ_{ult} (MPa)**	**Facing stress σ_{sf} (MPa)**	**Flexural stiffness D (N mm^2)**
LBF01	0.27	50	$3.5 \cdot 10^8$
LBF02	0.30	41	$3.5 \cdot 10^8$
LBF03	0.36	67	$3.6 \cdot 10^8$

Table 2.13: ABB C/C panel: combined LBF and SBF results.

Flexural stiffness D (Nmm^2)					
A	B	C	D	E	F
$0{,}99 \cdot 10^9$	$0{,}88 \cdot 10^9$	$0{,}98 \cdot 10^9$	$1{,}03 \cdot 10^9$	$1{,}18 \cdot 10^9$	$1{,}01 \cdot 10^9$
Transverse shear rigidity U (N)					
A	B	C	D	E	F
$2{,}7 \cdot 10^5$	$2{,}8 \cdot 10^5$	$2{,}7 \cdot 10^5$	$2{,}6 \cdot 10^5$	$2{,}1 \cdot 10^5$	$2{,}6 \cdot 10^5$
Core shear modulus G (GPa)					
A	B	C	D	E	F
0,254	0,272	0,255	0,248	0,204	0,249

The Carbon-Carbon sandwich substrate underwent mechanical characterization at TAS-I plants. Tests included: Long Beam Flexure (LBF), Short Beam Flexure (SBF), flatwise tension, flatwise compression, coefficient of thermal expansion (CTE), fiber content analysis. In parallel, complementary flexural and tensile properties of the facing material were determined on the separate quasi-isotropic (QI) laminate sample representing the facings of the sandwich panel. The number of specimens tested was limited due to the reduced dimensions of the available batches. Therefore neither the statistical treatment of results was possible nor the determination of the allowable values of the mechanical properties.

Facing tensile properties were determined in two perpendicular directions of the QI laminate, according to ASTM D3039. Results are reported in Table 2.10.

Facing flexural tests were performed according to ASTM D790 on the QI laminate. Measured average values of flexural properties were:

- Flexural chord modulus, $E_f = 30.3$ GPa.
- Flexural strength, $\sigma_{fM} = 105$ MPa.

All failures occurred by tension in the outer plies of the specimens.

Sandwich short beam flexure tests (Table 2.11) were conducted according to ASTM C393 3-point bending test method. As a matter of fact failure occurred at the core-to-facing interface, due to the intrinsic weakness of the adhesive bonding.

Sandwich long beam flexure was carried out in accordance to ASTM D7249, using a 4-point loading fixture with two different configurations (4-point quarter span, and 4-point third span). See Table 2.12 for results. All specimens failed by sudden shear crimping with facing-to-core disbonding, in the upper compression-loaded facings.

Sandwich flexural stiffness, transverse (through thickness) shear rigidity, and core shear modulus were computed from the combined results of LBF and SBF tests. Six different combinations were taken into account, and the average computed values for each of them are listed in Table 2.13.

Sandwich flatwise tension tests (Table 2.14) were performed according to ASTM C297, and the typical failure mode was described as adhesive failure of core-facing

Table 2.14: ABB C/C panel: sandwich flatwise tension.

Specimen	**Flatwise tensile strength (MPa)**	**Failure mode**
1	0.34	Facing-to-core bond
2	0.43	Facing-to-core bond
3	0.40	Facing-to-core bond
4	0.48	Facing-to-core bond
Average value	0.41	

Table 2.15: ABB C/C panel: sandwich flatwise compression.

Specimen	**Ultimate compressive strength (MPa)**	**Compressive chord modulus (MPa)**	**Failure mode**
A	0.65	38.6	Unsymmetrical, one edge
B	1.25	36.4	Uniform, four edges
C	0.95	16.6	Unsymmetrical, one edge
D	0.72	21.0	Unsymmetrical, one edge

adhesive, with the adhesive generally remaining on either the facing or the core surface, but not both.

Sandwich flatwise compressive properties were determined according to ASTM C365 (Table 2.15). Most of specimens showed asymmetrical compressive failure of the sandwich core, confined to one corner or edge of the specimens.

The approximate fiber content of the C/C material was determined by image analysis of sections of the sandwich facings. The same analysis also evaluated the presence of voids and cracks. The fiber volume fraction was calculated using the fiber area fraction (i.e. ratio of identifiable fiber area to total field area) measured on four fields. See Table 2.16 for results.

The morphological characterization of the material was made difficult by the diffused and irregular porosity, by the presence of large cracks running through the plies, and by the optical reflectances of the fiber sections and of the graphitized matrix, that were so close that the differentiation of the two phases required special attention and a careful setting of the analysis system.

The CTEs of the sandwich panel were measured in the honeycomb L and W directions using a laser interferometric system (Thales Alenia Space Cannes)

Table 2.16: ABB C/C panel: fiber content.

Specimen	**Field**	**Fiber area fraction (%)**	**Fiber volume content (%)**	**Void area fraction (%)**
S1	1	57	57	11
	2	49	49	9
S2	1	53	53	9
	2	49	49	10
	Average	52	52	10

Table 2.17: ABB C/C panel: CTE.

Sample	**CTE ($°C^{-1}$)**
CTE 11 (W direction)	$7.3 \cdot 10^{-7}$
CTE 12	$7.2 \cdot 10^{-7}$
CTE 13	$8.0 \cdot 10^{-7}$
CTE 21 (L direction)	$7.1 \cdot 10^{-7}$
CTE 22	$7.0 \cdot 10^{-7}$
CTE 23	$8.1 \cdot 10^{-7}$

between +25°C and +80°C. Three temperature cycles for each sample were run. The out-of-plane CTE was not measured because of sample size constraints due to the geometric characteristics of the environmental chamber. The measurement accuracy was $\pm 0.5 \cdot 10^{-7} °C^{-1}$. Results are listed in Table 2.17.

Regarding the thermal characteristics, Table 2.18 shows the properties of conductivity declared by Ultracor Inc. The in-plane properties are referred only to the skin. Instead, the properties for z direction are for the entire panel. The defect of this data is the lack of important properties of the measured sandwich panel, as cell size, skin thickness, fiber type, honeycomb foil gauge[7]...

Under a thermal point of view, the expected thermal properties were:

- In plane $K_{xy} \geq 300\ W/m/K$;
- Skin to skin axis $K_z \geq 40\ W/m/K$.

More details regarding estimated conductivity values of an actual Carbon-Carbon panel used by TAS-I for a MFS demonstrator are given in the chapter dedicated to testing.

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[7] Thickness of the foil that is the wall of every cell of honeycomb.

Table 2.18: Ultracor Carbon-Carbon thermal properties compared with other materials.

	Ultracor C-C H/C Panel	P-120 Facesheets Al. H/C	Al. Facesheets Al. H/C	Aluminum Plate
Thermal Conductivity (in plane) (W/m/K)	350	275	180	180
Density (g/cc)	0.27	0.2	0.3	2.7
Specific Thermal Conductivity (W-cm^3/mK-g)	1296	1375	600	66
Thermal Conductivity in Z-direction (W/m/K)	65	20	10	180
Specific Thermal Conductivity (W-cm^3/mK-g)	241	100	33	66

2.1.6 Kevlar fabric as a substrate

Kevlar (poly(p-phenylene terephthalamide) - PPTA) is an organic fiber (patened by DuPont) in the aromatic polyamide (aramid) family of fibres. Thanks to the aromatic character of the polymer backbone, that can provide high chain rigidity, materials belonging to this class of polymers show thermal and chemical stability, generally high melting points, high strength and modulus.

Kevlar products provide high temperature durability, low flammability, inherent dielectric strength and excellent chemical resistance, combined with high tensile strength and modulus. These products are well suited to the manufacturing of fabrics for protective clothing, paper in electrical uses, and high temperature filtration applications.

Most applications are based on forms of the polymer that can be prepared as wet or dry spinning of fibers, and solution casting of films. Commercially, fibers are available in a variety of forms, including continuous filament yarns of different deniers. Different forms of Kevlar, with sensible differences in physical and mechanical characteristics can be obtained from the same monomer: property difference is due to changes in the manufacturing process conditions for the high modulus and ultra modulus materials, which cause additional crystallinity, increased molecular alignment and hydrogen bonding between neighboring molecules. Kevlar K29, K129 and KM2 are very high strength, high toughness forms of Kevlar designed for improved ballistic fragmentation resistance and energy absorption capacity, while other forms of Kevlar (K49, K149) are typically used for structural applications.

Even if they have lower E_y (yarn stiffness, or slope of a quasi-static, tensile stress-strain curve) with respect to structural forms, the ballistic forms of Kevlar, and in particular the KM2, are characterized by relatively large values for both $\sigma_{y,fail}$ (yarn strength, or maximum stress attained on a tensile stress-strain curve) and $\varepsilon_{y,fail}$ (strain corresponding to maximum stress), which translates into a large value for toughness, or work per unit volume at failure.

Table 2.19: Single-yarn mechanical properties of ballistic and structural forms of Kevlar.

Yarn Type	E_y **(GPa)**	$\sigma_{y,fail}$ **(GPa)**	$\varepsilon_{y,fail}$
Kevlar49	112-135	2.9-3.6	0.024-0.028
Kevlar149	143-175	2.3-3.4	0.015-0.018
Kevlar29	70	2.9	0.036
Kevlar129	88-99	3.4-4.2	0.033
KM2	63-112	3.0-3.3	0.024-0.04

In order to reduce breakage of yarn during weaving, a sizing agent (usually a silicon-based polymer) is applied to improve abrasion resistance and decrease the hairiness of yarn. However, in aerospace applications, where contamination control is of paramount importance, it is important to scour (“desize”) the fabric after the weaving process.

As highlighted in the section of the previous chapter dedicated to inflatable structures, ballistic Kevlar is of great interest in the development of flexible habitats.

In Thales Alenia Space Italy, a research branch is developing new concepts for inflatable structures, and as a synergy with the Integrated Multifunctional Systems program, the possibility of including a multifunctional layer in the habitat wall is under evaluation. Application of flexible electronics over woven clothes substrates has never been evaluated before. Many aspects need to be taken into consideration, like the bondability of Polyimide over Kapton, the mutual CTE behaviour, and possible AIT issues.

2.1.7 Distributed electronics and digital buses

Onboard a spacecraft, a bus must meet a number of goals. It must provide the ability to acquire synchronous data frames from sensors with controlled latency, and to transmit synchronous data to actuators with controlled latency. Additionally, it must be capable of transfering asynchronous and isochronous data packets between nodes, and providing a symmetric medium access control service to nodes (i.e. each node can access the bus on demand). Furthermore, it must provide accurate distribution of time data and time reference pulse, and a safe implementation for a cross-strapping mechanism.

In general, user interfaces and systems that distribute data acquisition and control can take advantage of serial protocols to transport good amounts of data and information with very few wires. This reduces bundles of cabling to a mere few wires, lowering cost and increasing reliability. It also makes debug and expansion easier. In the space field this approach is still under evaluation, but the complexity and data volume generation of new missions are pushing the community in this direction. A satellite or rover avionic block diagram is presented in Figure 2.23. The number and complexity of interconnections can be easily noticed.

There are different candidate few-wires serial protocols: 1-Wire, I2C, CAN, SPI, and LIN. Even firewire, in its 4-conductors implementation, can be taken into account.

The idea of connecting all devices on the same line (it may be called “sensor bus solution”) has some clear advantages: for sure it enables harness reduction and as a consequence it brings mass saving; furthermore, it ensures higher flexibility during integration activities and allows to easily scale the network up and down. Of course, functional performances shall be granted and therefore some countermeasures shall be taken during design phase in order to solve some implicit drawbacks of this architecture. For example, a proper design must circumvent the catastrophic loss of all network due to a single failure (e.g. a single component malfunction could cause a short-to-ground failure of the signal line of the bus). Another example is the need to consider a redundant layout with physically separate circuits, with the purpose of avoiding the complete loss of functionality if a mechanical damage occurs.

To clarify recurrent expressions, when talking about N-wire interfaces, this wire number is the number of control lines. In addition to this, those interfaces generally need a common ground, which is the ground plane in circuit board applications and a separate wire in inter-circuit-board connections. On the bus, a device can be either a transmitter (i.e. it sends data to the bus) or a receiver (i.e. it receives data from the bus). Moreover a device can be either a master (if it initiates a transfer, generates clock signals and terminates a transfer) or a slave (if it is addressed by a

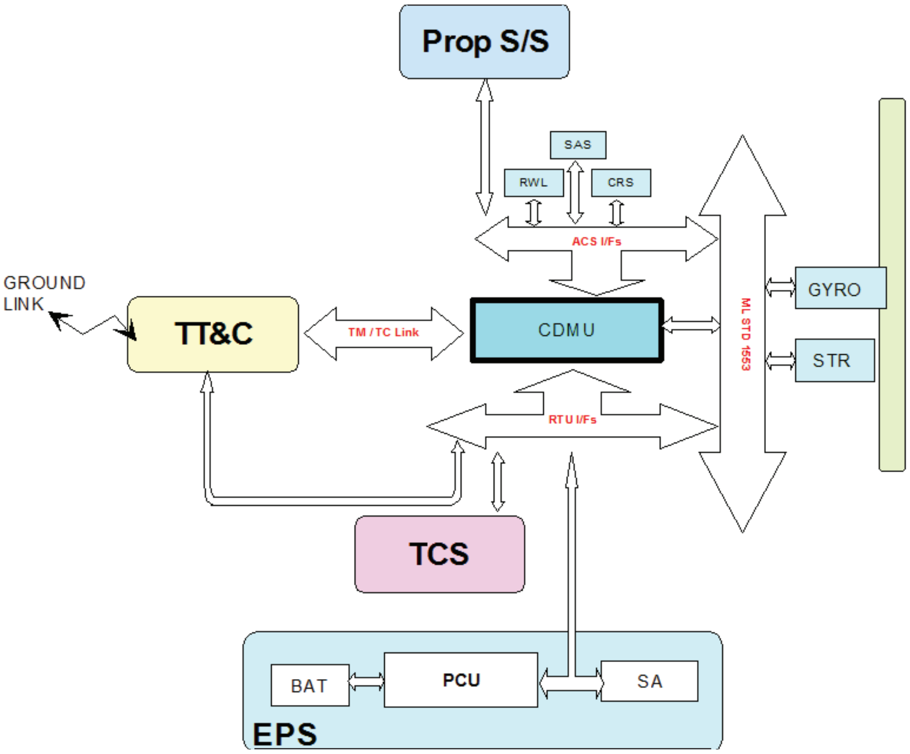

Figure 2.23: Example of a space system's avionic block diagram.

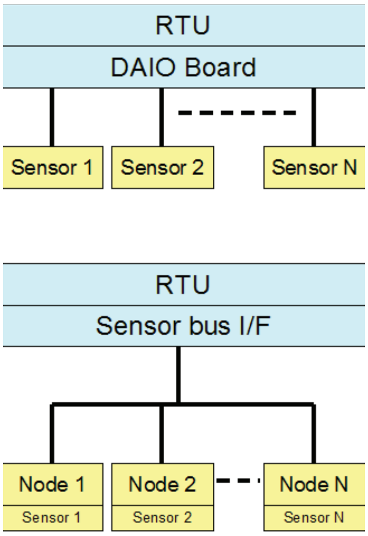

Figure 2.24: Classical solution (top) with each sensor hardwired to the RTU versus sensor bus solution (bottom) with each sensor connected to the RTU via a digital bus.

master). A bus is said to be multi-master if more than one master can attempt to control the bus at the same time without corrupting the message to be sent. In a protocol, especially on a multi-master bus, two procedures are of great importance: arbitration and synchronization. Arbitration is the procedure implemented to ensure that, if more than one master simultaneously tries to control the bus, only one is allowed to do so and the winning message is not corrupted. Synchronization is the procedure required to synchronize the clock signals of two or more devices. When talking of wired-and, the text refers to a binary model of dominant and recessive bits where dominant is a logical 0 and recessive is a logical 1.

This work takes into account possible candidate solutions for the communication network onboard a MFS, and compares their performance. A comparative summary is given in Table 2.21.

1-Wire bus

1-Wire is a registered trademark of Dallas Semiconductor Corp. (now, Maxim) for a device communication bus system that provides low speed data, signalling and power over a single line, albeit using a total of only two wires, one for ground, one for power and data. It is typically used to communicate with small inexpensive devices such as digital thermometers and weather instruments. A network of 1-Wire devices with an associated master device is called a MicroLan, that term being trademarked by Dallas.

One of the attractive features of the bus is that a device only needs two wires, data and ground. To accomplish this, each integrated circuit includes an 800 pF capacitor to power it from the data line. Some of the devices are available in tiny cans that look like small capacitors or watch batteries, in which packaging they are called iButtons. 1-Wire devices are also found mounted on printed circuit boards, with or without a 1-Wire controller. Sometimes the PCB is only there to support the 1-Wire device, but in many commercial applications, the 1-Wire device is just one of the chips creating the solution to some need. They are sometimes present in laptop and cellphone battery packs, for instance.

The Dallas 1-Wire network is physically implemented as an open drain master device connected to one or more open drain slaves. In any MicroLan, there is always one (and only one) master in overall charge. That may be a PC, or a microcontroller. The master initiates activity on the bus, simplifying the avoidance of collisions on the bus. Protocols are built into the software to detect collisions. After a collision, the master tries again to effect the required communication. The hardware level of the protocol is often performed by specially written software in the bus master device.

A single pull-up resistor is common to all devices: it acts to pull the bus up to 3 or 5 volts, and incidentally provides the power to the network of devices. Communication occurs when a master or slave asserts the bus low, that is, connects the signal line to ground through its output MOSFET. Datarates of 16.3 kbit/s can be achieved. There is also an overdrive mode which speeds up the communication by a factor of 10. Each 1-Wire chip has a unique 64-bit serial code buried within it. The least significant byte of the serial number is an 8-bit number that tells the type of the device. The most significant byte is a standard (for the 1-wire bus) 8-bit

CRC. In this way many devices can share the same bus. There are several standard broadcast commands, and commands addressed to particular devices. The master can send a selection command, and then the address of a particular device, and then the next command is executed only by the selected device. The bus also has an algorithm to recover the address of every device on the bus. Since the address includes the device type and a CRC, recovering the address list also produces a reliable inventory of the devices on the bus. The 64-bit address space is searched as a binary tree, allowing up to 75 devices to be found per second. This presence of a unique serial number also makes the chips suitable for use as a key to open a lock, arm and deactivate burglar alarms, authenticate computer system users, operate time clock systems, and other similar uses.

With 1-Wire protocol it is possible to utilize long (greater than 100 m) cables effectively. Up to 300 meter long buses consisting of simple twisted pair telephone cable has been tested by the manufacturer. It will however require adjustment of pull-up resistances from say 5 kΩ to 1 kΩ.

The location of devices on the bus is sometimes significant. For these situations, the manufacturer has a special device that either passes through the bus or switches it off.

1-Wire is similar in concept to I2C, but with lower data rates and longer range.

To sum up the benefits of 1-Wire protocol, one can highlight that being parasitically powered (power is derived from signal bus) and having a single contact sufficient for control and operation, 1-Wire devices are unmatched in their ability to provide key functions to systems where interconnections must be minimized. This benefit is amplified by the multidrop capability of 1-Wire (it supports multiple devices on single line, identified by a unique ID factory-lasered in each one of them) Moreover, 1-Wire components have an exceptional ESD performance.

I2C bus

I2C is a simple bidirectional multi-master serial bus for efficient inter-IC communication. It has been invented by Philips and it is used to attach low-speed peripherals to a motherboard, embedded system, cellphone, or other electronic device. I2C is appropriate for peripherals where simplicity and low manufacturing cost are more important than speed. For example, common applications of the I2C bus are display data channels, hardware monitors and diagnostic sensors, volume control for speakers… Peripherals can also be added to or removed from the I2C bus while the system is running, which makes it ideal for applications that require hot swapping of components.

All I2C-bus compatible devices incorporate an on-chip interface which allows them to communicate directly with each other via the I2C-bus. Usually, the CMOS ICs in the I2C-bus compatible range offer a number of interesting features: they have extremely low current consumption, high noise immunity, wide supply voltage range, and wide operating temperature range.

I2C uses only two bidirectional open-drain lines, Serial Data Line (SDA) and Serial Clock (SCL), connected to a positive supply voltage via a current-source or pull-up resistor. Typical voltages used are +5 V or +3.3 V although systems with other voltages are permitted. In simple terms, pulling the line to ground is considered a logical zero while letting the line float is a logical one. In reality, due to the variety of different technology devices (CMOS, NMOS, bipolar) that can be connected to the I2C-bus, the levels of the logical 0 (low) and 1 (high) are not fixed and depend on the associated level of VDD. Input reference levels are set as 30% and 70% of VDD; VIL is 0.3 VDD and VIH is 0.7 VDD (it can be useful to remember that some legacy device input levels were fixed at VIL = 1.5 V and VIH = 3.0 V). When the bus is free, both SDA and SCL lines are high. The output stages of devices connected to the bus must have an open-drain or open-collector to perform the wired-AND function.

The assignment of slave addresses is one weakness of I2C. The I2C reference design has a 7-bit or a 10-bit (depending on the device used) address space. The 7 bit addressing is the most widespread and, unfortunately, it supports just a very small number of devices. In fact, seven bits is too few to prevent address collisions between the many thousands of available devices. Moreover, different devices from different manufacturers come with hard coded slave address or with an address that is configurable in a small range only: indeed manufacturers may provide pins to configure a few low order bits of the address while arbitrarily setting the higher order bits to some value based on the model. This limits the number of devices of that model which may be present on the same bus to some low number, typically between two and eight. These bad habits can sometimes lead to address clashes. In addition to these logical limitations, one must consider that the maximum number of nodes is also physically limited by the total bus capacitance of 400 pF, which restricts practical communication distances to a few meters.

As we have already mentioned, the bus is a multi-master one which means that any number of master nodes can be present. Additionally, master and slave roles may be changed between messages. An important consequence of this is that multiple nodes may be driving the lines simultaneously. If any node is driving the line low, it will be low. Nodes that are trying to transmit a logical one can see this, and thereby know that another node is active at the same time. When used on SCL, this is called “clock stretching” and gives slaves a flow control mechanism. When used on SDA, this is called “arbitration” and ensures there is only one transmitter at a time.

I2C supports a limited range of speeds. Nowadays it has 4 operating speed categories. Serial, 8-bit oriented, bidirectional data transfers can be made at:

- Up to 100 kbit/s in the standard-mode (Sm).
- Up to 400 kbit/s in the fast-mode (Fm).
- Up to 1 Mbit/s in fast-mode plus (Fm+).
- Up to 3.4 Mbit/s in the high-speed mode (Hs-mode).

The 400 kbit/s, 1 Mbit/s, and 3.4 Mbit/s speeds are more widely used on embedded systems than on PCs. Furthermore, hosts supporting the multi-megabit speeds are rare and many devices don’t even support the 400 kbit/s speed. Support for the Fm+ speed is more widespread, since its electronics are simple variants of what is used at lower speeds. Fm+ is also appreciated because bus speed can be traded against load capacitance to increase the maximum capacitance by about a factor of

10. Note that the bit rates quoted are for the transactions between master and slave without protocol overheads (communication includes a slave address and perhaps a register address within the slave device as well as per-byte ACK/NACK bits) or clock stretching (devices are allowed to stretch clock cycles to arbitrarily low frequencies to suit their particular needs, which can starve bandwidth needed by faster devices and increase latencies). So the actual transfer rate of user data is lower than those peak bit rates alone would imply. Bus capacitance also places a limit on the transfer speed, especially when current sources are not used to decrease signal rise times.

Because I2C is a shared bus, there is the potential for any device to have a fault and hang the entire bus (e.g. if any device holds a line low, it prevents the master from sending START or STOP commands to reset the bus). Thus it is common for designs to include a reset signal that provides an external method of resetting the bus devices.

Because of I2C inherent limits (address management, bus configuration, potential faults, speed), few bus segments have even a dozen devices. It is common for systems to have several such segments dedicated to different device classes.

CAN bus

CAN-bus is a serial communication bus standard for real-time applications originally developed at Robert Bosch GmbH and designed to allow microcontrollers and devices to communicate with each other without a host computer. CAN is a message-based protocol, designed specifically for automotive applications but now also used in other areas such as industrial automation and medical equipment, primarily due to the low cost of some CAN controllers and processors.

CAN is a multi-master broadcast serial bus, able to work with data-rates up to 1 Mbit/s and with excellent error confinement capabilities (it has an extensive and unique error checking mechanisms).

The devices that are connected by a CAN network are typically sensors, actuators, and other control devices. These devices are not connected directly to the bus, but nested in a CAN node. A CAN node is composed of 3 basic elements: a host processor, a CAN controller, and a transceiver.

The host processor decides what received messages mean and which messages it wants to transmit itself. It is the interface for various sensors, actuators, etc. The CAN controller, while receiving, stores received bits serially from the bus until an entire message is available, which can then be fetched by the host processor (usually after the CAN controller has triggered an interrupt). While sending, it transmits serially onto the bus the bits generated by the host processor. The CAN transceiver is the physical layer interface: it acts both in reception (it adapts signal levels from the bus to levels that the CAN controller expects and has protective circuitry that shelter the CAN controller) and in transmission (it converts the signal received from the CAN controller into a signal that is sent onto the bus).

In a CAN bus all the nodes are connected to the same two wires, labelled CAN-high (CANH, CAN+) and CAN-low (CANL, CAN-). It is not required to have a common ground signal among the communicating devices. The standard electrical implementation is formed by a multi-dropped single-ended balanced line

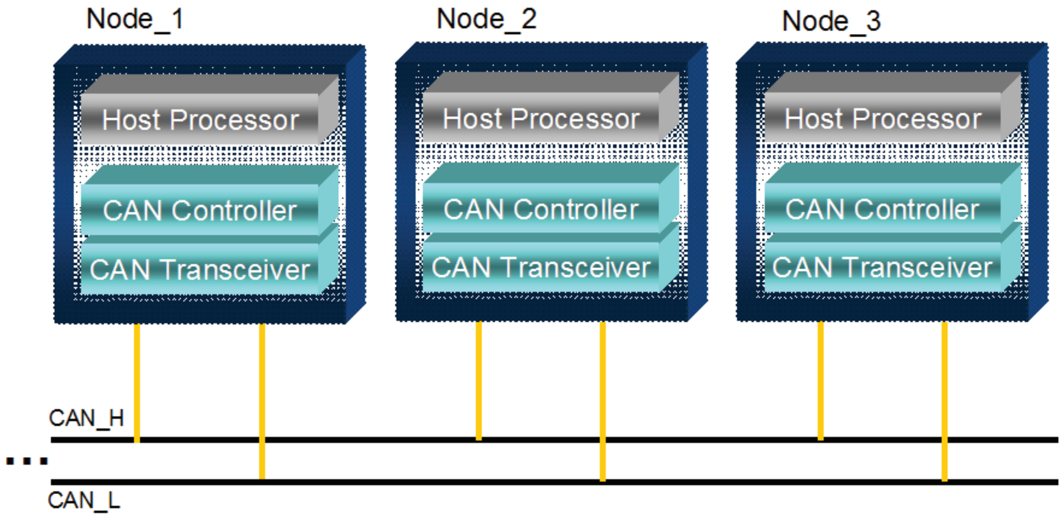

Figure 2.25: CAN nodes on the bus (copyright MOXA).

configuration with 120 ohm termination resistor at each end of the bus. In this configuration a dominant state is asserted by one or more transmitters switching the CAN- to 0 V and (simultaneously) switching CAN+ to the +5 V bus voltage, thereby forming a current path through the resistors that terminate the bus (as such the terminating resistors form an essential component of the signalling system and are included not just to limit wave reflection at high frequency). As a result, in a normal situation, the two wires carry a two-level signal, perfectly specular, and whenever one is high the other is low. Best practice determines that CAN bus balanced pair signals be carried in twisted pair form within a shielded cable and it is this precaution that helps to keep RF emissions to a minimum.

Each node is able to serially send and receive messages, but not simultaneously. A message consists primarily of an ID (identifier), which represents the priority of the message, and up to eight data bytes. The communication mechanism is referred to as priority based bus arbitration: between two competing messages, the one with the more dominant ID will overwrite other nodes' less dominant IDs, so that eventually only the dominant message remains and is received by all nodes. Each node in a CAN network has its own clock, and no clock is sent during data transmission. Synchronization is done by dividing each bit of the communication frame into a number of segments.

An interesting characteristic of the CAN bus is that it's possible to add nodes to the bus without reprogramming the other nodes to recognize the addition or changing the existing hardware. This can be done even while the system is in operation. The new node will start receiving messages from the network immediately. This is called hot-plugging. Another useful feature built into the CAN protocol is the ability of a node to request information from other nodes. This is called a remote transmit request, or RTR.

Theoretically, CAN protocol can link up to 2032 devices (assuming one node with one identifier) on a single network. But accounting to the practical limitations of the hardware (transceivers), it may only link up to 110 nodes on a single network. The standard defines up to 32 nodes per network. Bus maximum length is dependent

Table 2.20: Different bus lengths and corresponding maximum bit rates for CAN.

Bus length	Maximum bit rate
40 m	1 Mbit/s
100 m	500 kbit/s
200 m	250 kbit/s
500 m	125 kbit/s
620 m	100 kbit/s
1 km	50 kbit/s
6 km	10 kbit/s
10 km	5 kbit/s

on the operational speed, and bit rates up to 1 Mbit/s are possible at network lengths below 40 m. Decreasing the bit rate allows longer network distances (e.g., 500 m at 125 kbit/s), down to a minimum speed of 5 kbps at a length of up to 10 kilometers. These numbers are determined for a noise free environment. The bus line should be as close as possible to a straight line to keep reflections to a minimum.

CAN bus communication is usually very reliable. It has high immunity to electromagnetic interference and has the ability to self-diagnose and repair data errors. Actually, the use of differential signalling (i.e. with two complementary signals sent on two separate wires) gives tolerance of ground offsets and resistance to EMI (since external interferences affect similarly both wires, the difference between the voltages remains unchanged and the bus is quite insensitive to those external interferences). The very high noise immunity is achieved also by ensuring that the differential impedance of the bus is maintained at a very low level using low value resistors (120 ohms) mounted at each end of the bus. The bus is also immune to single unit fault: faulty nodes are automatically dropped from the bus. This helps to prevent any single node from bringing the entire network down, and thus ensures that bandwidth is always available for critical message transmission. Additionally, CAN is able to operate in extremely harsh environments. The devices can often work even in case of bus being severely miswired. For example, communication can still continue (but with reduced signal to noise ratio) even if either of the two wires in the bus is broken, or either wire is shorted to ground, or either wire is shorted to power supply. This reliability is among the properties that made CAN bus the current standard in difficult environments, with wide temperature ranges, and very varying environmental situations.

Some numerical examples

In the last years there has been a strong push toward the introduction of few-wires protocols in the space field. For example, the ESA Onboard Computer and Data Handling section, responsible for research and development activities and for supporting ESA projects and missions in the field of spacecraft data systems and related architectures, is currently studying and evaluating I2C utilisation on-board

Table 2.21: Candidate buses: comparison.

	I2C	**1-Wire**	**CAN**
Power consumption	Two transceiver are needed	Only one transceiver is needed	
Network extension	20 meter	Hundred meter is achievable	Kilometer is achievable
Network topology	=	=	Single line is preferred
Max. n. of devices	Up to 20 nodes	Up to 100 nodes	Up to 124 nodes
Data transmission	Up to 400 Kbps (3.4 Mbit/s in Hs-mode)	Around 12 kbps	Length dependent (up to 1 Mbit/s)
Mass reduction	4 wires are needed (including GND)	Only 2 wires are needed (SDA and GND)	Only 3 wires are needed (VDD, CANH, CANL) GND is optional
Flexibility	Several components for different applications	Restricted application	Robust and suitable for many applications
Existing space application	Already existing in space application, even if not qualified	Hobo sensor	Exomars (study)

spacecraft and in health monitoring solutions.

To better explain the reason pushing this qualification effort, it is worth looking at three numerical examples. The results are summarized in Table 2.22.

A first example of the benefits achievable with the use of few-wires serial buses comes from the Herschel satellite. Herschel is an ESA scientific satellite launched in 2009. Its objective is to reach the L2 orbit (Langrangian Orbit, 1500000 km far from Earth) and to measure the deep space noise of the universe with its telescope.

According to Herschel's documentation, 299 sensors are distributed in the whole satellite; each sensor is connected to the acquisition board via a dedicated wire. Of these, around 150 ÷ 200 sensors are thermistors used by the thermal control system. Several typologies of wires are used for the sensors' connections. The total length for the wiring of all sensors is around 1.8 km (note that these values are not mere estimates, but measured quantities). The cost of a space qualified twisted shielded pair wire is around 1500 euro/m. Present technology would lead to have a total cost of 2.6 millions euro just for sensors' connections, and a mass of about 16 kg for the required wiring.

A multifunctional architecture with embedded sensors and digital bus would drastically reduce the costs and volumes, because most of the harness would be embedded in the structure. The harness would be reduced to a few tens of meters with a cost of about 50000 euro, and a mass of about 2 kg. Moreover, it is important to remember that a reduction in terms of wiring mass also means a reduction of propellant required by the launcher and this in turn increases again the cost saving. The mass of the whole spacecraft would then be reduced of ∼1% and the cost for launcher (due to propellant) would be reduced consequently. The two main envisaged cost saving are then rising from cabling reduction, and launcher cost reduction.

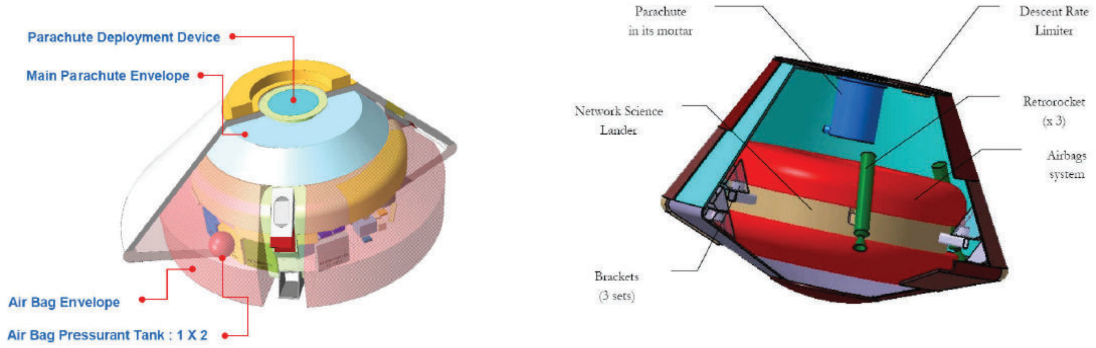

Figure 2.26: Exomars 2016 EDL concept (copyright ESA).

Another interesting case study is the estimation of mass impact for an embedded heat shield instrumentation with direct connection to an acquisition board, like the one initially foreseen for the Exomars EDL demonstrator (see Figure 2.26). This demonstrator was one of the many intermediate stages underwent by the turbulent Exomars program: it was planned as a 2016 Mars orbiter-lander mission aimed at demonstrating safe entry, descent and landing on Mars, and at providing atmospheric and dynamics measurements during EDL. For that reason, the lander system was equipped with an heat shield instrumentation suite, which had a purely scientific rationale and was lately discarded from the design because of mass constraints. The instrumentation comprised 113 sensors: 63 thermocouples, 25 pressure sensors, and 25 thermistors.

The sensors were designed to be embedded in the structure, with each of them linked to the acquisition board via a dedicated analogue connection. The estimated average length for each connection was then of ∼6 m, for a total length of 678 m and a total mass of about 9 kg. In this case the wiring mass could be reduced down to 600 g and a total length of 30 m. The cost would be again drastically reduced of about 95%: from 1 million euro to 50000 euro.

A third field for comparison is that of exploration rovers. For these vehicles, the main goal is the allocation of all the avionics and payloads in a very compact size. For rover modules, the saving stemming from a multifunctional approach would not be measurable in terms of hundreds of meters of cabling saving, but it would mainly consist in the reduction of design complexity. In fact, the main body of exploration vehicles like MSL Curiosity or Exomars RM is extremely crowded with harness, thermal hardware, and electronics boards (see Figure 2.27). It is extremely difficult to find a good configuration for all the components that need to be enclosed in such a reduced space, and obviously assembly and integration activities are extremely challenging.

For exploration rovers, the multifunctional systems approach with few-wires serial communication protocols can be adopted to embed TCS sensors and related wires in one or more panels. A total of about 30÷40 sensors and associated wiring can be hidden into two panels of 60 cm x 60 cm. For this quantitative study, let's consider 40 sensors that need to be acquired by a board about 1 m far. The connection from each sensor to the acquisition board would be ∼1 m long. Moreover, the command of heaters can be performed via dedicated bus, and this would result in further mass saving. The estimated number of heaters is around 13 nominal elements and 13 redundant elements, each of them located 1 m far from the power distribution unit. Summing up the various contributions, an integrated structure will save tens of meters of cabling. In this case the saving would be mostly measured in terms of volume reduction and mass reduction that can be used for additional payload allocation.

Summing up, the main advantages of the usage of few-wires protocols are:

- Reduction of wiring design and integration complexity.
- Lighter mass.
- Additional volume available for scientific payloads.

Table 2.22 gives a numerical comparison of the two different approaches: traditional design versus integrated multifunctional design with few-wires digital bus.

Figure 2.27: MSL Curiosity: overview of the crowded chassis and complex integration procedures (copyright NASA/JPL).

Table 2.22: Comparison between different avionic and communication architectures.

	Herschel satellite (sensors and wiring)		Exomars (heat shield instrumentation)		Exomars (Rover module)	
	Traditional	**MFS**	**Traditional**	**MFS**	**Traditional**	**MFS**
Mass	16 kg	2 kg	9 kg	600 g	high (actual figure is confidential)	low (compared to traditional solution)
Volume	1.8 km of cable	$\sim$ 30 m of cable saved volume available for scientific payload	678 m of cable	30 m of cable	$\sim$ 60 m of cable	$\sim$ 1 m of cable saved volume available for scientific payload
Cost	300 000 EUR	3 000 EUR	67 800 EUR	3 000 EUR	high (actual figure is confidential)	low (compared to traditional solution)
Manufacturing	Connection of 299 single cables	Connection of a few buses	Connection of 113 single cables	Connection of a few buses	Connection of $\sim$ 60 single cables	Connection of a few buses
System complexity	high	low	low	medium	high	low
Assembly, integration and verification	Verification is easier (simpler fault localization)	Assembly and integration are easier (fewer steps)	Verification is easier (simpler fault localization)	Assembly and integration are easier (fewer steps)	Verification is easier (simpler fault localization)	Assembly and integration are easier (fewer steps)
Modularity	not possible	possible	NA	NA	NA	NA

2.2 Advanced BreadBoard (ABB)

In Thales Alenia Space Italy, the ABB research activity was the direct follow-on of DBB. Its aim was a further improvement of thermo-mechanical performance, and the integration of electronics and diagnostic functions. Since the design activity is not strictly part of this thesis, this section summarizes only the main characteristics. For a detailed description see [73] and [7].

The demonstrator consists of a Carbon-Carbon panel equipped with two thin, flat, flexible motherboards bonded face to face on one skin. The motherboards are equipped with a temperature monitoring system, including sensors and acquisition system (one-wire technology), miniaturized DC/DC converters and power resistors to be used both for thermal control of surrounding hardware and as dummy thermal loads to test the panel's heat rejection capability.

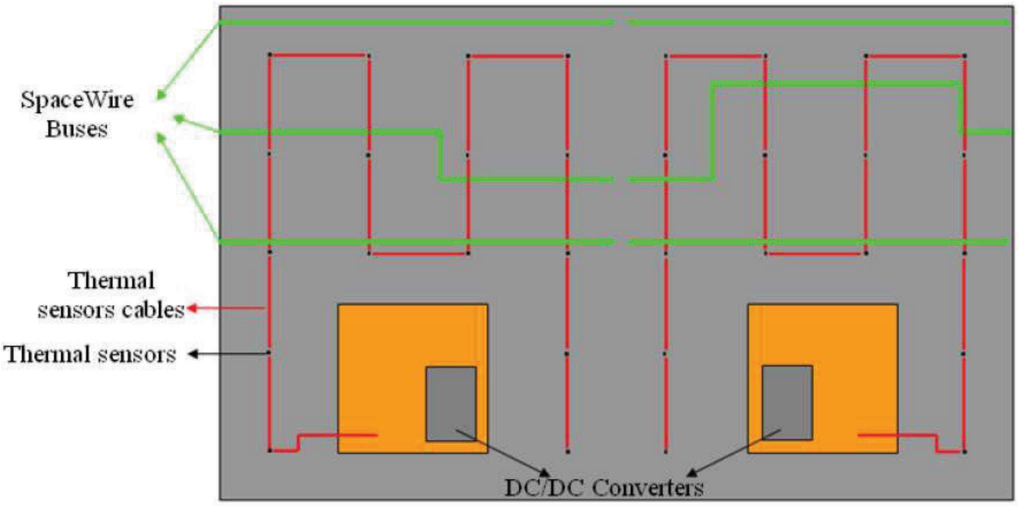

Figure 2.28: Initial concept for ABB panel: motherboards with DC/DC converter slots, one-wire flat cable, sensors and bus cable (SpaceWire) can be easily pointed out.

Besides an innovative sandwich structure, ABB presents distributed electronics. As can be seen in Figures 2.28-2.30, the ABB surface skin has been equipped with two independent, symmetrical monitoring circuits which consists of two identical but symmetric flat and flexible motherboards (the orange squares in Figure 2.28), each one connected to a Flat Flexible Cable (FFC, the thin red serpentine line in Figure 2.28) via a top contact connector (Tyco 84953-4, mounted on the motherboard). A 1-Wire-to-USB interface (Dallas DS2490S) mounted on each motherboard sends queries to every sensor and delivers data to a PC using a USB connector (Molex 56579-0576). The overall dimensions of each motherboard are 150 × 150 mm. The motherboards are flexible and very thin, because they are made of a material called Dupont Pyralux®AP 9121 (Flexible Polyimide), which is composed of three layers:

- 35 μm of copper (bottom layer);
- 50 μm of dielectric;
- 35 μm of copper (top layer): this layer is copper-plated, reaching a final thickness of $45 \div 47$ μm.

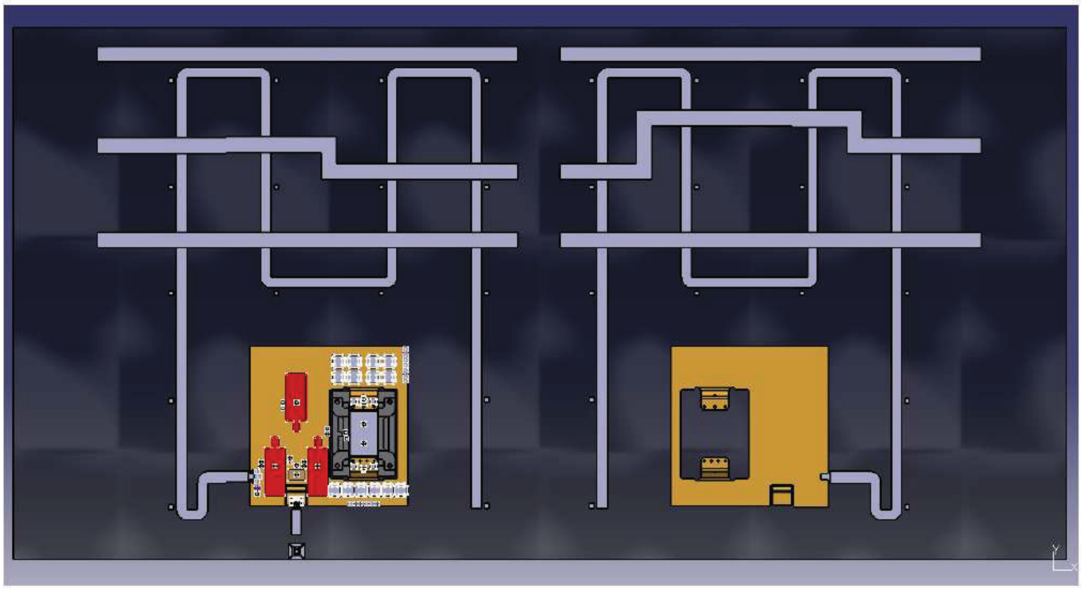

Figure 2.29: Catia® plane view of ABB concept.

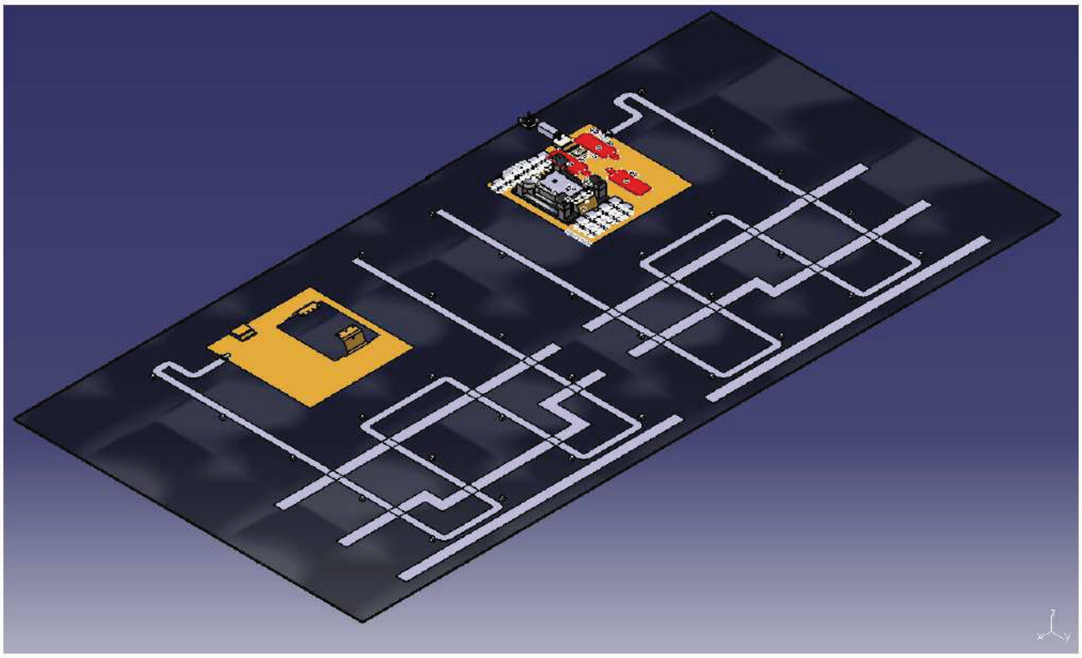

Figure 2.30: Catia® axonometric view of ABB concept.

Table 2.23: Summary of main electronic component installed on ABB motherboards.

Component	**Function**	**Inoperative range**		**Operative range**	
		Min T	Max T	Min T	Max T
Dallas DS9503	ESD Protection	-55	+125	-40	+85
Dallas DS2490	USB to 1Wire	-55	+125	0	+70
MAXIM MAX8881	ultra-low supply curr.	-65	+165	-40	+85
VICOR MICRO V110C28M100BF	DC-DC converter	-65	+125	-55	+100
DS18B20U	Temperature Sensor	-55	+125	-55	+125
Minco Kapton HK5582R5.3L12A	Heater	-200	+200	-200	+200

The MBs provide local interconnects and house the surface-mounted electronic components needed to control a distributed sensor network. Heaters (the red rectangles on motherboards) are added on each motherboard in order to protect surrounding circuitry during thermal tests and to simulate thermal loads. Each motherboard has independent electronics for data acquisition purpose, therefore it is equipped with an integrated circuit for sensor data acquisition and also a DC/DC converter. This DC/DC converter transforms 110 V into 28 V with a maximum power of 100 W: these characteristics were chosen to comply with the International Space Station (ISS) power line voltage. The power supply provides power to the three heaters while also offering thermal load simulation. Easy dismount or replace of main bulky electronic components is provided via specific clamps that connect the single removable item to the flat, distributed circuitry.

Moreover, ABB has a distributed sensor network made of 40 temperature sensors (Dallas DS18B20, black dice in Figure 2.28) located throughout the panel (on skin, motherboards and components) based on one-wire technology; sensors are connected by a flat polyimide flex cables, and managed via a micro-controller mounted on the flat PCB.

Heaters and temperature sensors are not wired through traditional cables but with a technology quite similar to the one used for the motherboard: a thin film of polyimide with embedded electrical copper strips. Heaters are located on the main MBs, while temperature sensors are distributed both on the motherboards and on the rest of the panel.

Motherboards are laser cut for different reasons:

- to enable contact of certain components with the supporting structure: temperature sensors (since they shall monitor the underlying panel skin), and DC/DC converter (since its aluminium baseplate must ensure good thermal coupling with the skin);
- to enable electronics integration: DC/DC converter's pins soldering, ground connection;
- to make the PCB conformable to particular geometries: connect bulky DC/DC converter, adapt to USB wedge-shaped shim.

All circuit components (except the DC/DC converter) are surface mounted on the motherboards. To allow electrical connections, some zones without solder mask (unprotected) are provided for each component (solder pads). Table 2.23 lists the most relevant items.

2.3 STEPS Smart Skin

Previous TAS-I demonstrators of multifunctional structures included the idea of transforming bulky and cumbersome electronics into flat motherboards. In particular, wide use was made of MCMs and flex interconnects. An evolution of the flat motherboard led to the smart skin concept.

The smart skin explores the areas concerning: distributed heating, distributed health monitoring, flexible distributed electronics: it is a flat and flexible layer (in

Kapton or other flexible material) integrating health monitoring functions (sensor network: temperature, strain, vibration, pressure. . .), surface-mounted electronics, heating devices completely embedded into the skin, signal/power distribution network, cutouts for electronic box allocation.

As already mentioned, nowadays the integration of space systems has come to a point in which device accommodation, together with monitoring, power and signal harness, saturates available volumes and pose challenges to design activities. Electronics is accommodated in cumbersome dedicated housing, cables connecting units fill the whole available volume, and often the installation of thermal hardware must face an extremely crowded environment. From this point of view, a smart skin-based MFS not only grants a reduction of volumes allocated for specific service functions, leaving a higher percentage to payload budgets, but also allows postponing some design choices, leaving room for more flexibility in architecture definition.

Basically, in the smart skin concept, functions traditionally committed to different subsystems are embedded in a single flexible stratum, able to follow the final shape of structural panels acting as an outer, multifunctional layer. Moreover, it is worth noticing that such a motherboard can be carved in odd and irregular shapes and can be easily adapted to non-planar surfaces.

From a MFS point of view, the smart skin can constitute the outer layer of multifunctional composite panels. The idea of localizing multifunctional potentialities in a light, highly integrated, flexible layer is a mean of innovation in MFS field, where, up to now, only bulky solutions have been proposed. As already mentioned, this feature would allow changes in structural panels layout until the very last phases of design activity. This is due to the possibility to develop the panel and the external skin as two separate products and to adapt the shape of the latter to the architecture of the former as a final step.

The possibility to supply power and transmit data using embedded conductor lines would drastically reduce the need for wiring harness. An analogous technology would enable certain spots on the skin to behave just like standard heaters and to maintain nearby electronics in the operative temperature ranges. This would eliminate the need to manually install heaters after product integration.

Moreover, to highlight further potential benefits of smart skin application, it is worth noticing that a single integration step which accommodates the multifunctional layer would replace the reiterated installation of several pieces of equipment, each one dedicated to a single well defined task.

The smart skin concept described in this thesis, addressing the use of miniaturized, distributed, commercial electronics with standard interfaces, would reduce acquisition costs even if it would add drawbacks in terms of EMI-EMC validation. In addition, a smart skin would be a medium to achieve capillary on-line monitoring (to assess temperature and stress for large composite panels). One of the key points that characterize the smart skin is the implementation of few-wire protocols in order to build the monitoring network and allow signal distribution. As mentioned in the dedicated section, there are different potential data protocols for a few-wires network, each one with its pros and cons. In past research activities, TAS-I privileged Dallas®1-Wire, but now a new interest arose for I2C and CAN as possible alternatives to 1-Wire.

A technology like the smart skin is suitable to a number of applications in space and aeronautics industry and, generally speaking, in all fields where mass and volume reduction are required in order to have an economically and technologically viable product.

The activities that have been addressed in order to have a full smart skin demonstrator are the following:

- Definition of requirements
- Survey and selection of technologies to be included in the smart skin for integration of heating functions, integration of distributed electronics and flexible interconnections, integration of health monitoring functions
- Materials trade-off and selection: flexible foils, adhesives, printed circuit techniques…
- Definition and development of manufacturing processes
- Hardware and software design of the smart skin modules
- Design of a technology demonstrator (smart skin + supporting panel)
- Manufacturing and assembly of smart skin and supporting panel
- Definition and execution of a verification test plan

Due to the experimental nature of the activity, smart skin requirements were fixed keeping into account the expertise and technological limitations of suppliers. The initial requirements for the smart skin are hereafter summarized. Each motherboard shall be able to:

- Receive input from a central computer
- Acquire the sensors' data
- Process the sensors' data
- Activate the heaters mounted on itself
- Exchange the sensors' data and heaters' status with a central computer

The smart skin monitoring capabilities must include at least temperature sensing and vibration/acceleration sensing. It shall be possible to depopulate the motherboards in order to reduce the number of sensors and the number of heaters, without any rework or change in the base PCB.

The smart skin shall work correctly when exposed to a temperature range of $-40°\text{C} \div +50°\text{C}$ and withstand different pressure conditions: ambient conditions, 900 to 1100 hPa, and vacuum conditions (10^{-5} Pa). The smart skin shall withstand a relative humidity (RH) varying within a minimum of 35% and a maximum of 60%.

The nominal power line voltage onboard the PCBs shall be 28 V, but the motherboard shall work normally within the range of 27.5 V to 30 V.

The smart skin shall be a thin and flexible motherboard and shall not exceed the following dimensions: 420 mm x 300 mm.

Electrical signal must be routed on flexible PCB traces specific for signal line. Power supply must be routed on flexible PCB traces specific for power supply.

The MB shall accommodate reworkable or replaceable electrical and electronic hardware. Whenever possible, electronic components shall be mounted directly on the flexible motherboard substrate, therefore they shall be surface mount devices (SMDs). Relatively bulky elements shall use dedicated fixtures to accommodate them, and to connect them to the mainly bi-dimensional circuit. For specific components other fixtures can be used to avoid permanent bonding to the motherboard or to the underlying support structure, allowing future replacement or inspections (e.g. a "deck" that holds a dismountable unit in place).

Heaters shall be integral part of the motherboard design. Each heater embedded in the smart skin shall dissipate 4 W ± 1 W (at 28 V nominal voltage). Heater activation and deactivation must be electrically controlled via solid state switches. Each heater must be equipped with one to three temperature sensors to be used for heating functionality monitoring. Specific logics, based on data collected by these temperature sensors, shall turn the heaters on and off. Control logics must be able to manage each heater as an independent unit. The smart skin shall be able to withstand the total system's heater thermal power, defined as the the power dissipated (at the same time) by all the heaters of all motherboards.

The smart skin power density shall never exceed in any point 0.33 W/cm^2 at 28 V nominal voltage. Each motherboard shall allocate at least 4 heaters and 4 temperature sensors.

At least an access point to the motherboard internal communication bus must be available for the following purposes:

- Monitoring of bus functionality
- Connection of an external controller in possible passive motherboards (in case of a depopulated MB, built with just sensors and heaters, or in case of a failure of the MB own controller)
- Accommodation of bus-extender connections to create a network made of many different smart skin modules

A control station/user interface shall be available to upload firmware to the microcontroller and characterize control logic parameters. The microcontroller's control logic can be developed using model base design tools[8]. Control models can be converted into C code suitable for microcontroller by using automatic code generators [9].

A number of flexible motherboards are installed on a support panel to create the final demonstrator. The support panels used for the smart skin technology demonstrator have the following maximum envelope dimensions: L = 500 mm, W = 1000 mm, T = 25 mm. The main smart skin demonstrator shall be composed of

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[8] Like Matlab/Simulink®.

[9] Like Real Time Workshop®.

at least 3 flexible motherboards. The various motherboards shall be interconnected via flexible jumpers.

Due to available manufacturer expertise, the choice for PCB materials was steered toward conventional flex solution, in particular copper layers for power supply and signal line, Inconel layers for heater implementation (since they offer higher resistance than copper layers), and Kapton layers for insulation.

For cost reduction purposes, electronic components were selected among non-space qualified components belonging to families that already have or can easily produce space qualified equivalents.

Under a software point of view, the smart skin had to demonstrate the ability to work as a stand-alone module, acquiring data from the environment and actuating peripherals according to given functional control strategies, but also to work as a part of a wider network formed by other smart skins and an external control unit, which is representative of either an on board computer during a mission or a ground support equipment during integration and test. Therefore, besides the physical MFS demonstrator (panel + smart skin), a further ancillary problem to be faced was the definition and development of an interface for breadboard tests. To improve portability, it was decided to use a standard PC as an external controller. The smart skin architecture derives from similar systems used in aerospace, automotive, railway sector. Multiple smart skin modules form a network where all smart skin nodes are interconnected via CAN bus. In fact, two communication buses were identified within the smart skin system: an internal communication bus, and an external communication bus. The internal bus allows the following functionalities:

- Microprocessor to sensors communication
- Microprocessor to IO expander communication

The external bus allows the following functionalities:

- Microprocessor to remote controller communication
- Master microprocessor to slave microprocessor communication (in case of slave processor availability)

Materially, the smart skin concept consists of a 210 x 300 mm flexible modular motherboard, made of copper layers separated by insulating polymeric layers and interconnected by means of plated through holes (PTH). The smart skin is equipped with the following components:

- One microcontroller (MCU)
- One I2C I/O expander
- One DC/DC converter
- Four embedded heaters
- Power logic (MOS) for control of heaters' power supply

- I2C bus as connection bus between microcontroller and sensors (intra-board)
- Seventeen I2C temperature sensors, distributed across the board
- One analog accelerometer (2 axis)
- CAN bus controller and transceiver for the connection between different microcontrollers (inter-board communication) and with external control computer (communication with control system or GSE)
- RS232 controller and interface for monitoring and debugging purposes

Two descriptive system block diagrams are depicted in Figures 2.31 and 2.32, while Figure 2.33 shows the corresponding electrical schematic.

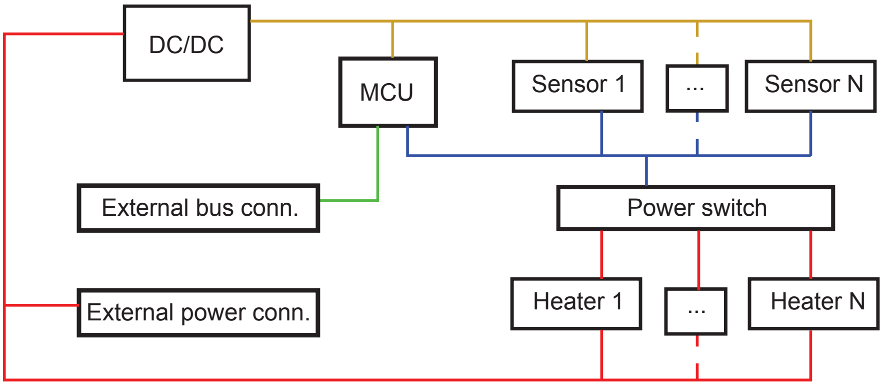

Figure 2.31: Conceptual smart skin schematic. Red line represents high voltage external power, orange line is for low voltage regulated power, blue line is for intra-motherboard I2C communication bus, and green line signifies external inter-motherboard CAN or RS232 communication bus.

The power supply is designed for 28V DC input and capable to give 5V DC output, which is the main voltage source for all the components on-board, except the heaters that use 28V source. It utilizes a LM5010 from National Semiconductor, a high-voltage 1A step-down switching regulator capable of handling input voltages from 8V to 75V.

As already specified, the communication between smart skin board and external devices is achieved using CAN bus protocol. A MCP2551 from Microchip has been chosen as the CAN bus transceiver that act as the interface between Main Controller Unit (MCU) CAN port and the CAN bus communication lines.

The controller block is composed by a main controller unit (PIC18F2580), an I/O expander (MCP23008), an accelerometer (2 axis, ADXL321), an operational amplifier for interfacing the accelerometer and MCU, and 3 digital temperature sensors (MCP9803). The PIC18F2580 from Microchip is a 8-bit microcontroller with 32 kB of flash memory, 1536 bytes of RAM, and 256 bytes of data EEPROM. It also provides 1 EUSART, 1 ECAN, 1 I2C/SPI bus interfaces, and 8 channel of up to 10-bits resolution Analog to Digital Converter (ADC). In addition, the MCP23008 is utilized as an I/O expander in order to control the on-off switch for each heater. It communicates with the MCU by standard 2-wire I2C protocol.

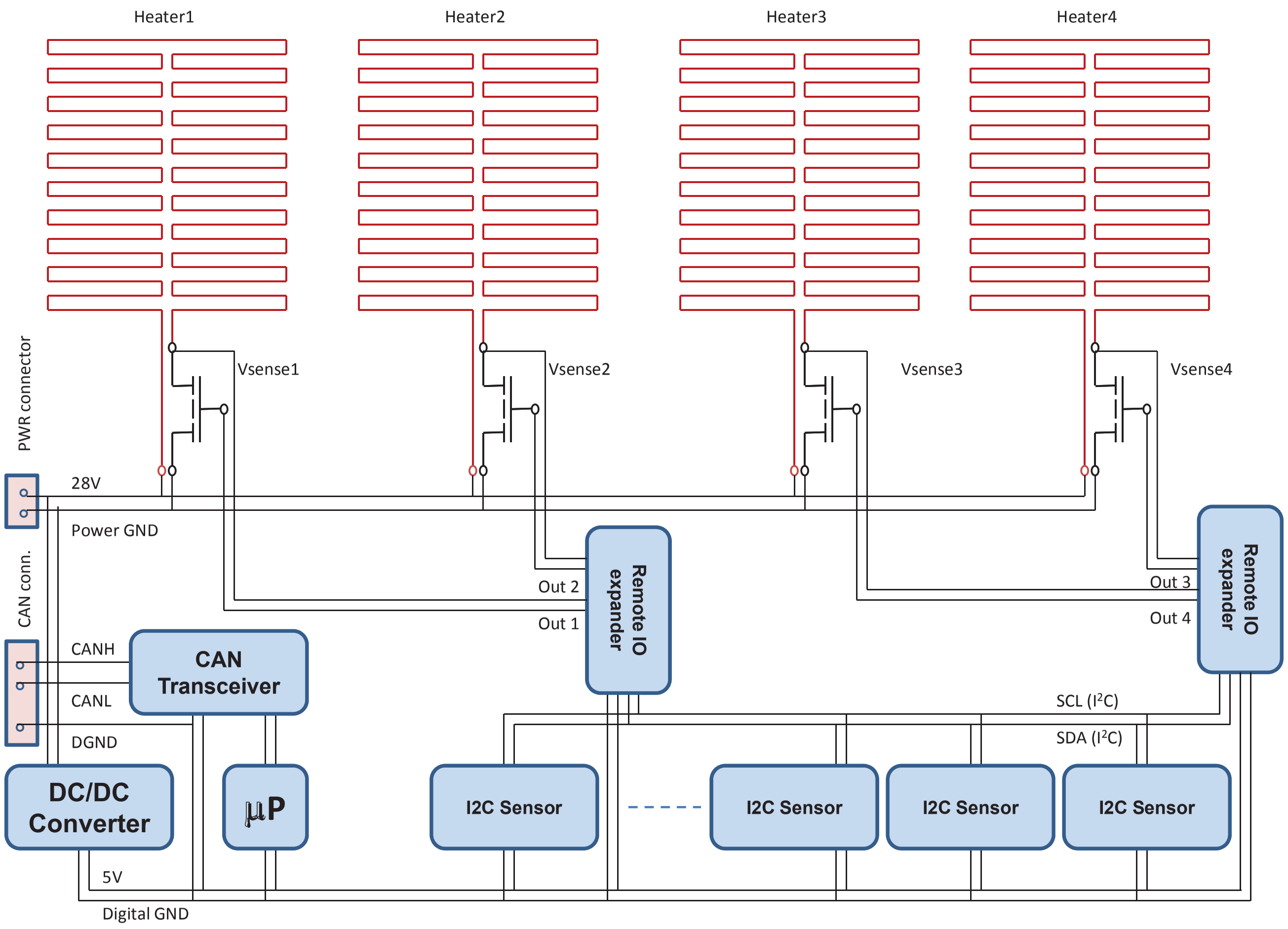

Figure 2.32: Conceptual smart skin schematic. Power supply and communication connections.