Database definition to support a model-based system engineering approach for reusable access to space design

DATABASE DEFINITION TO SUPPORT A MODEL-BASED SYSTEM ENGINEERING APPROACH FOR REUSABLE ACCESS TO SPACE DESIGN

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INTRODUCTION

In the last decades, space exploration has played a very important role for mankind, which has exploited it for scientific, communication and even defence purposes, to name a few. In this scenario, the frequency of access to and re-entry from space has steadily increased [1] and it is projected to continue its growth in the future caused by the deployment of new satellites and the advent of space tourism, leading to an increase in the number of requests for access to space and re-entry [2]. The use of reusable access to space and re-entry vehicles, which are the subject of this paper, will not only allow to perform the required missions, but it will also help to reduce their life cycle and environmental impact.
Since these systems can be built in a great variety of configurations and their development is influenced by different disciplines, the Model-Based Systems Engineering approach is considered particularly suitable for their design process. Model-Based Systems Engineering (MBSE) is an innovative approach to systems engineering for complex systems design focused on managing stakeholders' requirements, synthesizing designs, and verifying and validating systems throughout their lifecycle in a collaborative environment [3]. In contrast with traditional Systems Engineering (SE), which relies on documentation, MBSE supports the system design thanks to the exploitation of digital models, which allow the designer to have a unified view of the effect of different disciplines and needs. This approach effectively reduces the development time and costs by improving collaboration between teams and reducing the risk of inconsistent documentation. Additionally, MBSE ensures a full traceability of the requirements throughout the product's lifecycle. Despite the MBSE approach can be considered as being mainly focused on the development of the methodology for the design of complex systems, its implementation has to be complemented by the use of a unified language and proper tools to enhance team cooperation. Moreover, it should be supported by the exploitation of data for the development, analysis and validation of the system through an effective data management system. The last issue is addressed by knowledge-based systems (KBS) which provide reasoning capabilities and complex problem-solving thanks to the exploitation of a knowledge base built onto an explicit representation of knowledge stored in databases [4]. Various types of databases can be employed. In the aerospace sector, the most effective representation of data is obtained using the relational database model proposed by E. F. Codd in 1970 since it has the ability to capture mutual dependencies among elements of a database. The relational data model can be managed with relational database management systems (RDBMS) which often employ SQL (Structured Query Language) for accessing the database. The data in RDBMS is stored in two-dimensional tables independent from each other which are logically interconnected by means of unique keys assigned to each row or connection tables. This structure simplifies the storage of large amounts of data by eliminating any parent-child relation while at the same time preserving relations and dependencies among the elements [5].
Given the importance of data management in the design workflow of MBSE, the focus of the paper is to build a database of all available configurations of launch and re-entry vehicles to support the design of new concepts for future reusable vehicles for access to and re-entry from space. Since a great variety of concepts have been analysed throughout the history of space exploration, the database aims at gathering in one place all reusable access and/or re-entry vehicles either operational or researched and their technical specifications. This will then serve as a solid baseline for the derivation and sizing of new sustainable launch and re-entry configurations according to the stakeholders' needs and technical requirements identified at the beginning of each project. Finally, in the interest of creating a reliable and comprehensive

tool, the new configurations derived at each time can be added to the database and considered for the design of the next vehicles.

OVERVIEW OF EXISTING DATABASES

Some databases related to space exploration vehicles have already been created in previous works and projects. One of the most relevant for this work is the TREx database created by the European Space Agency (ESA) to collect data related to Human Landing Systems. This database has been built according to the relational data model using the SQL language within several contracts. The last delivered version of TREx is not only a collection of design data for every project mentioned but it also contains the hierarchy of the technologies and building blocks involved, along with subsystem data and their interconnections. A key characteristic of the TREx database is the presence of specific tables for user traceability, that allow to keep track of changes and of the user who performed it, as well as to control the revision process [6].
Another example of a database is represented by the HyDat (HYpersonic DATabase) developed by PoliTo under ESA contract specifically for the classification of MicroLaunchers to support the iDREAM integrated multifidelity methodology [6, 7]. Analogously to TREx, the HyDat database has been built using SQL language with the aid of MySQL, an open-source and widely used RDBMS technology due to its flexibility and high interoperability with other modelling tools [8]. The first version of HyDat has been created to be a well-organized collection of data, easy to upload, modify and update through a user-friendly interface. The objective of the work was dual: on one hand, the database was conceived to support the generation of technology roadmaps for hypersonic, re-entry and future reusable space transportation systems, while simultaneously serving as a basis for generating statical analysis at different design levels, thus being a supporting tool for the design of such vehicles [7]. The construction of this database has been carried out through subsequent steps by integrating functionalities already present in TREx, such as user traceability and the building block hierarchy. In HyDat the user can insert various past or ongoing projects, as well as information regarding the schedule, the budget, the partners involved and their nationality, and a log of changes in the consortium, delays and modifications of budget. Particular attention has been given to organizing technology-related information hierarchically, through the definition of Technology Areas, Technology Subjects, Technologies, and technical characteristics each one associated with a high, medium or low level [7]. In the last delivered version of HyDat (iDREAM version), some tables of the database have been reorganized in order to make its structure as general as possible in preparation for a future extension to other case studies [6]. The work presented in this paper uses the iDREAM version of the HyDat database as a reference and it aims at extending it to reusable access to space and re-entry vehicles.

METHODOLOGY

iDREAM HyDat database

The last delivered version of the HyDat database has a convoluted structure that can be organized into four main areas. The first one concerns user traceability: different tables are created to keep track of every user of the database, its privileges, and the actions performed in order to be able to verify at any moment the work done. These tables are also helpful for any supervisor to perform the review process, which is also logged into dedicated tables.
The second area is related to the definition of mission concepts i.e. the nature of the mission, which could be for instance, LEO exploitation for several purposes, Lunar exploration, Mars exploration and so on. Each mission concept is associated with the respective level of technological advancement, which in turn is related to the TRL. In this way, it is possible to include in the database a variety of mission concepts ranging from operative (or high TRL) missions to demo (or low TRL) missions and future work. The mission concepts are then linked with projects, which in turn are connected to building blocks and technologies hierarchy. The term “building block” refers to the system configuration developed in each project, e.g. entry module, spaceplane, communication network, refuelling module to name a few. Building blocks are then associated with the operational capabilities required for each mission.
Finally, the third area is designated for the collection of design data for the vehicles designed within the different projects at the system and subsystem level. The structure described allows every project and building block to be related with the subsystems employed to perform their respective mission concept.
The connections among tables have been performed either by directly connecting the table through the use of *keys* in case of one-to-one connections or by using connection tables for many-to-many and one-to-many connections [6].
The iDREAM version of the HyDat database is not shown here for privacy reasons.

Derivation of new categories for reusable access to space and re-entry vehicle

An extensive literature analysis concerning past and present development of reusable access to space and re-entry vehicles has led to grouping these systems into high-level categories based on their main design characteristics. These categories could be seen as the mission and operational requirements of the MBSE design approach. From a mission perspective, reusable access to space and re-entry vehicles can perform ascent, re-entry or ascent and re-entry missions, both manned and unmanned. More specifically, ascent missions can be carried out by means of a horizontal take-off, a vertical take-off or an air launch while for re-entry missions the landing can be horizontal or vertical. Some additional requirements can arise from the specific payload of the mission. From the configuration point of view, reusable access to space and re-

entry vehicles can be constituted by multiple stages, each performing a different type of take-off and/or landing employing winged, non-winged and other innovative shapes, e.g. waveriders. On a lower level, reusable space transportation systems often employ advanced propulsive systems, such as Air-Turbo Rocket (ATR), Dual-Mode Ramjet (DMR) and other combined-cycle engines, which are often the enabling technology of the project.
The high-level characteristics presented have been useful to identify the areas of the HyDat database that require updating for its extension to reusable access to space and re-entry vehicles. In the following paragraphs, the modifications proposed will be examined more in detail grouping them by area of intervention.

Operational capabilities

For the purpose of this work, operational capabilities are considered in relation to the type of ascent and re-entry, which can be vertical or horizontal, and to the type of mission, i.e. manned or unmanned. Concerning this subject, the last delivered version of HyDat contains the general categories “Cargo entry” and “Manned entry” for the re-entry on Earth and “Cargo take-off/lift-off and ascent” and “Manned take-off/lift-off and ascent” for the ascent phase from Earth. These classes of operational capabilities implicitly include both the horizontal and vertical modes. For the sake of preventing to overstretch the database, the table related to the operational capabilities has been kept unchanged.

Vehicle Configurations

As mentioned before, reusable access to space can have different configurations. The last version of HyDat already contains a list of possible configurations, among which the general categories “entry module”, “spaceplane”, and “launchers” could be applied also to the case study of this work. However, they are not sufficient to capture the variety of possible configurations of access and re-entry vehicles. This is important not only for the sake of a comprehensive classification but also because the configuration significantly impacts the design process and the related input variables of these vehicles. Therefore, the following categories have been added to the building blocks table:

- Entry Capsule/Probe
- Entry Conic/Biconic Module
- Lifting Body Entry Module
- Blended Wing-Body spaceplane
- Waverider spaceplane

Design data specific for Reusable Access to Space and Re-Entry Vehicles

In the HyDat database, the data useful for the design process is contained in dedicated tables. Since the last delivered version focused on collecting the data for Human Landing Systems and MicroLaunchers, it is necessary to create additional columns for the characteristic data of reusable access to space and re-entry vehicles. The current HyDat version already provides the possibility to track the number of stages and the related propulsive characteristics, as well as some dimensions (i.e. length, width, height). As a consequence, the additional information included concerns data more specific to the case study, such as the aerodynamic efficiency (L/D), the lift and drag coefficients, and the reference surface area. Furthermore, an indicator of the level of reusability of each stage, both for already stored data and for new data, has been inserted in the design data tables, as explained in the subsequent dedicated paragraph.

Number of stages

As mentioned in the previous paragraph, the last version of HyDat already entails the possibility to include the number of stages, which can be used also for reusable access to space vehicles, thus preventing the need for modifications related to this subject.

Propulsion systems

The delivered version of HyDat collects the propulsive data of different rocket engines used in traditional launchers. Therefore, the propulsive subsystems table has been enriched with the data referring to the advanced propulsive systems typically mounted on reusable access to space and re-entry vehicles, such as ramjets, scramjets, and other advanced combined cycle engines, i.e. ATR, DMR, and SABRE-like engines.

Reusability

An important aspect missing from the last delivered version of HyDat is the level of reusability of the vehicles. Since the focus of the work is to collect reusable access to space vehicles and re-entry, it is necessary to include an indication of reusability in the database. For this purpose, a new table has been created and populated with the degree of reusability associated with a unique ID. In particular, based on the literature review the following categories have been defined:

- Expendable, referring to single-use vehicles or building blocks, which are either left in space or burn in the atmosphere

- Partially reusable, concerning vehicles or building blocks which can be reused in some parts
- Reusable, regarding vehicles or building blocks which can be reused after a proper service and refurbishment.

The reusability table has then been connected to the design data table with a one-to-one connection using as key a specific ID. This allows the level of reusability to be linked to the single projects by specifying the type of reusability for each stage involved. In addition, the reusability table has been connected also to the building block table by means of a bridge table. Although this is not strictly required for the design process of reusable access to space and re-entry vehicles, it offers the user the possibility to visualize whether a specific building block can be reusable and eventually link it to the related project, where the reusability of each stage is specified.

The modified version of HyDat is not reported here for privacy reasons.

Data fill-in

The literature analysis provides an overview of all past and ongoing projects related to the design of reusable access to space and re-entry vehicles, as well as the data useful for the design of such systems, which has been collected into MS Excel files. Using the MySQL Workbench interface, the data has been inserted into the last version of HyDat using MySQL [8]. In case of some data is not available or applicable for the specific project, the corresponding cell can be filled with "NULL".

APPLICATION EXAMPLE

Once the database is updated, the user can either employ it using to a top-down or a bottom-up approach. An example of query is provided in the following.

Concerning the top-down approach, the user can visualise the projects related to a configuration of its interest. For instance, assuming that the user wants to design a re-entry vehicle in lifting body configuration, it is possible to see the projects associated to the development of such vehicles and the related design data. For this purpose, it is necessary first to identify the tables storing the desired information and their mutual connection. In this case, the table containing the list of possible configurations of space transportation systems is linked to the projects table which in turn is connected to the table storing the design data of each system and subsystem. In this application, the type of configuration can be considered a parameter used to select only a subset of projects and data. Since the modified version of HyDat does not yet have a Graphical User Interface, the search process must be performed either through a SQL script in MySQL Workbench or from the command prompt. For example, a first query could be used to obtain as output a table containing only the projects related to the design of lifting body re-entry vehicles. Subsequently, it is possible to select a subset of the design data related to one or more of the projects mentioned. The design data table is connected with other tables containing information about materials, propellants, and subsystems, as well as the level of reusability.

Considering a bottom-up approach, the user can start by selecting a specific vehicle to subsequently derive higher-level information such as the configuration of the system. For example, assuming that the user has chosen as a reference one or more vehicles based on their design data values, it is possible to derive the corresponding projects and the vehicle configuration. For example, a first query can provide the user with the name of the projects corresponding to the selected subset of design data, from which the configuration corresponding to those projects can be obtained exploiting the connections among the tables.

CONCLUSIONS AND FUTURE WORK

The paper presented a set of proposed actions for the update of the existing HyDat database, originally developed for MicroLaunchers and Human Landing Systems, to the case study of reusable access to space and re-entry vehicles based on high-level characteristics that impact their design. From the operational point of view, since the horizontal and/or vertical take-off and landing capabilities of such vehicles were already included in the database, no modifications have been carried out. Concerning the possible configurations, referred to as building blocks, the existing list has been enriched with the categories typical of reusable space transportation systems since they significantly impact the design process and the variables involved. Regarding the design data, some additional columns have been included in the table for the storage of the design data of reusable access to space and re-entry vehicles, especially concerning their aerodynamic performance and their reusability. Finally, a table related to the reusability level of such vehicles and their systems has been added to the existing database.

Given the variety and quantity of reusable access to space and re-entry vehicles, the update activities of the HyDat database require continuous work and subsequent steps in order to make the database comprehensive and widely applicable. Therefore, future activities should encompass the refinement of the categories and changes performed if needed, as well as the inclusion of data related to subsystems when available. The work should focus on the definition of costs and technology readiness of these concepts, which often constitute the main obstacle to construction and deployment of these systems. Moreover, for the purpose of creating a multi-purpose tool, the database should be extended to other space transportation systems.

Finally, the current updated version of the database can be accessed using the MySQL language through MySQL Workbench or command prompt. Even though this is an open-source tool, it requires the user to know the syntax of the language in order to consult and modify the database. Therefore, a Graphical User Interface should be developed in order to enhance the user experience and improve accessibility.

REFERENCES

[1] Sirieys, E., Gentgen, C., Jain, A., Milton, J., de Weck, O., Space sustainability isn't just about space debris: On the atmospheric impact of space launches, MIT Science Policy Review, 3 (2022) https://doi.org/10.38105/spr.whfig18hta

[2] Morgan Stanley, Space: Investing in the final frontier, https://www.morganstanley.com/Themes/global-space-economy. Accessed July 2024.

[3] Alten, MBSE – L'ingegneria dei sistemi basata sui modelli, https://www.alten.it/2022/09/13/mbse-ingegneria-sistemi-basata-modelli/. Accessed July 2024.

[4] Brusa, E., Calà, A., Ferretto, D., *Systems engineering and its application to industrial product development*, Springer International Publishing, 2018

[5] Vidhya, V., Jeyaram, G., Ishwarya, K.R.. *Database Management Systems*. Alpha Science International, New Delhi, 2016

[6] iDREAM Maintenance, Technical Note, 2022, restricted access.

[7] N. Viola, S. Cresto Aleina, R. Fusaro, V. Vercella, "Space systems engineering tools for technology roadmapping activities: TrIS, technology roadmapping strategy, and HyDaT, database on hypersonic transportation systems", 69th International Astronautical Congress (IAC), Bremen, Germany, 1-5 October 2018

[8] Oracle, MySQL website, https://dev.mysql.com/