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Abstract— **An experimental methodology to validate tracked vehicle dynamics through a multibody model is presented. The methodology was conceived and implemented jointly by the Vehicle Dynamics research group of the Politecnico di Torino and Corps of Engineers officers serving at the Italian Army Experimentation Centre (CEPOLISPE). Some original solutions were applied in relation to the impossibility of making any modifications to the tracked vehicle hull. The instrumentation setup permits to measure the motions of the suspended mass (hull), the speed of the sprocket wheels and the displacement of the road wheels that transmit the vehicle dynamics to the tracks. The instrumentation is completed with wiring, connections and fasteners, designed to connect IMU, wire potentiometers and pick-ups to the data acquisition system and power supply. The measurement system was effectively validated through various track tests, leading to the results expected at the design stage. A subset of experimental results with validation is here presented, while a larger set of experimental tests will be later used for the validation of a tracked vehicle multibody model developed in ADAMS ATV software.**

Keywords—tracked vehicle, vehicle dynamics, measurements, digital twin, experimental validation.

I. Introduction

The study of the dynamic behavior of tracked vehicles covers a wide range of applications including the verification of operational limits in terms of mobility as well as determining the dynamic conditions to which on-board electrical and electronic equipment may be subjected. The topic of mobility is made particularly complex by the operating conditions of tracked vehicles on terrain of potentially any consistency and shape. Tracked vehicles [1] have significantly different physical and constructional characteristics compared to wheeled vehicles, which attributes to their ability to excel in off-road mobility with higher payloads, but they share similar design and verification tasks related to NVH performance ([2], [3]) and safety requirements for stability to avoid the risk of rollover [4]. The robustness of mounting and support solutions for electrical and electronic equipment must meet the requirements of standards such as MIL-STD 810H, as investigated durability tests [5] for a military off-road vehicle. Both requirements necessitate testing under conditions that closely replicate operational conditions as closely as possible, so that the vehicle assembly can be declared fit for operation. However, given the variety of equipment in military vehicles [6], it is especially beneficial to have digital twins (DTs) suitable for studying, even prior to the actual adoption of vehicle upgrades, the effect on performance as outlined above. It therefore becomes essential to acquire the ability to model the dynamic behavior of such vehicles even in any terrain conditions, together with the ability to validate them experimentally using solutions that are both robust and goal-oriented. It is a common practice to develop multi-body models [7], [8] as DTs of tracked vehicles to evaluate their performance in different conditions. In the last years, the authors have already proposed digital twins for investigating the vertical dynamics of a tracked vehicle [9], evaluating the influence of the track chain tensioning [10], through a lumped parameter model developed in the customized FEM software LUPOS [11]. Similarly, analytical studies have been conducted for characterizing the steering behavior [12], designing controllers to control the cornering vehicle response [13] by simulating typical maneuvers for handling analysis. Instead, from an experimental point of view, different works are available in literature regarding the analysis of suspension system [14] and noise and vibration measurements [15].

The unique characteristics of the application context required tailored experimental solutions, as modifications such as adding fixing holes to the instrumented vehicle were not allowed. Additionally, the test conditions were extremely aggressive, making the use of wireless instrumentations or insufficiently robust sensors and wiring up to the acquisition system impractical. In this paper a solution adopted to instrument a tracked vehicle and measure quantities in order to validate a multibody model of its dynamic behaviour under a set of operating conditions, is presented. The experimental results are compared with those obtained in simulation.

II. EXPERIMENTAL VEHICLE SET-UP

An original methodology was defined to instrument a tracked vehicle in order to acquire the experimental data required to validate its multibody model. Essentially, the instrumentation includes:

- an Inertial Measurement Unit (IMU) + GPS antenna with RTK correction to measure the accelerations, speeds and position of the sprung mass;
- a pair of inductive pick-up sensors to detect the rotation speed of the sprocket wheels. The original solution is the design of an ad hoc support structure that allows each pick-up to be positioned without having to make modifications to the vehicle's hull or work on components such as the powertrain;
- three pairs of potentiometric wire sensors, each installed on one side of the vehicle, to detect the suspension travel. The original solution in this case is the adoption of support brackets attached to the hull by means of high-density magnets and a technique for attaching the ends of the wire potentiometers to the suspension arms, in a position close to the wheels, which is both simple and robust.

The instrumentation is completed with the necessary wiring and connections. All the sensors are powered by a battery located in the vehicle's interior and the signals are acquired by an acquisition system. The main difficulty posed by the measurements concerned the physical connection, via wiring, of the wire potentiometers and pick-ups. The former are located within the operating volume of each track and the latter are close to the engine exhaust, therefore subject to high temperature. With regard to the potentiometer signals, an original methodology was adopted based on laying the power and signal cable of each potentiometer in such a way as to make it adhere to the hull and force it to bypass the track on the inside of the track itself, then pass over it and, from there, enter the interior where the data acquisition unit has been set up. As far as the pick-up is concerned, the fixing support was completed with a two-stage sensor holder, which is therefore suitable for both an initial coarse positioning of the sensor and a second one characterized by the need to position the sensor with sufficient precision to achieve correct switching. In addition to this, the solution adopted made it possible to ensure a very robust protection of the sensor both from the point of view of resistance to possible shocks related to vehicle dynamics and thermal aspects.

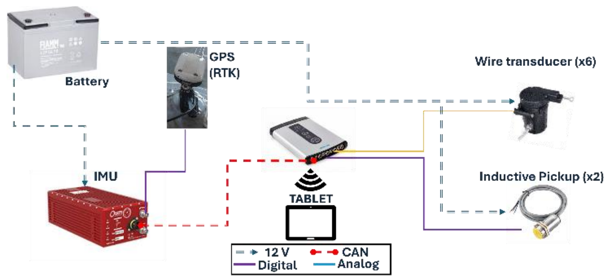

Figure 1: Schematic overview of the measuring system.

One aspect that proved to be essential was the special care taken to prepare wiring suitable for the difficult test conditions. To do this, a plurality of extension cables were used, equipped with automotive connectors, which are not only resistant to dust but also to mud and water. All the materials used are commonly available on the market. In Figure 1, a schematic overview of the measuring system, together with the corresponding wiring configuration, is reported.

The measured acquired from the whole set of sensors are synchronized and saved locally through a SIEMENS SCADAS XS device. In particular, the data from the IMU and GPS is acquired through CAN protocol, the 6 wire transducers are connected to the SCADAS analog input meanwhile the tacho interfaces are selected for measuring the frequency of the two inductive pickup signals. The SCADAS is remotely controlled with a tablet that is responsible for the data acquisition project setup and the recording management.

All measured quantities are then post-processed through a dedicated software toolchain elaborated in Matlab® environment which executes the following tasks:

- Plot and save the raw and processed data, thus providing a useful monitoring tool during experimental sessions;
- Elaborate the time histories of the angular speeds for the left and right sprocket wheels to be used as input values for the simulation run;
- Compare and validate the simulation results against the experimental measurements.

An overview of the vehicle experimental setup is shown in Figure 2.

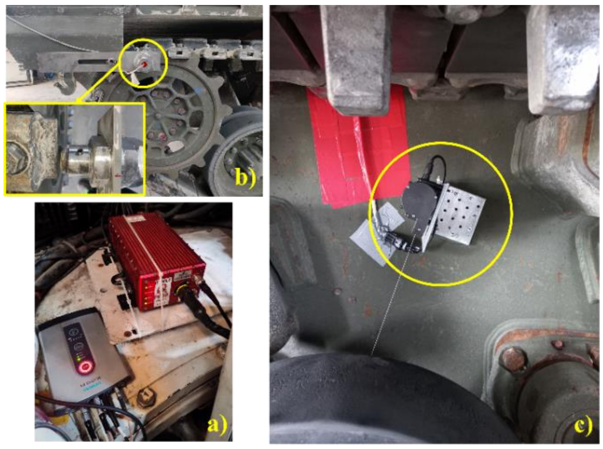

Figure 2: Vehicle experimental setup: a) IMU with SCADAS XS, b) pickup with ad hoc supporting structure and c) wire transducer with magnetic support.

The pickup sensors are installed, through a dedicated adjustable mounting support, as close as possible to one of the track rotating elements meanwhile the wire transducer is magnetically attached to the lateral hull surface by means of L-shaped commercial supports. The IMU is installed internally, rigidly attached to the vehicle hull and in a position as close as possible to the vehicle center of gravity.

III. TRACK TESTS

The tests were conducted on the CEPOLISPE concrete tracks in dry conditions. The data were acquired according to an experimental test plan which covered:

- braking and acceleration, at different accelerator and brake pedal positions, for longitudinal dynamics analysis;

- constant speed maneuvers on longitudinal and transverse sloped roads;
- crossing maneuvers over stepped obstacles
- steering pad maneuvers

An example of data logging is reported in Figure 3 where a longitudinal dynamics test is executed by imposing a constant 70% accelerator pedal followed by a constant 70% brake pedal.

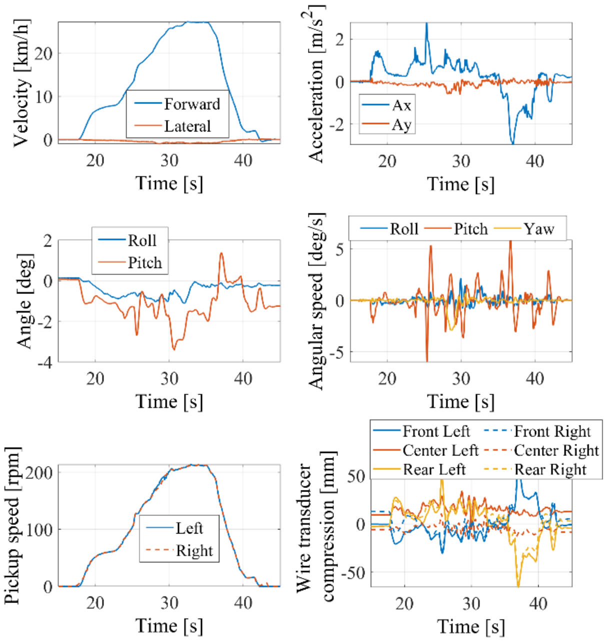

Figure 3: Example of data acquisition during a maneuver with a 70% constant accelerator pedal followed by a 70% constant brake pedal

The results are shown in terms of vehicle speeds (forward and lateral), accelerations (longitudinal and lateral), orientations (roll and pitch), angular speeds (roll, pitch and yaw), pickup speeds and wire transducers placed in three different positions at right and left vehicle sides. All the data shown in the figure are processed with dedicated low pass filters to remove sensor noises and high frequency dynamics.

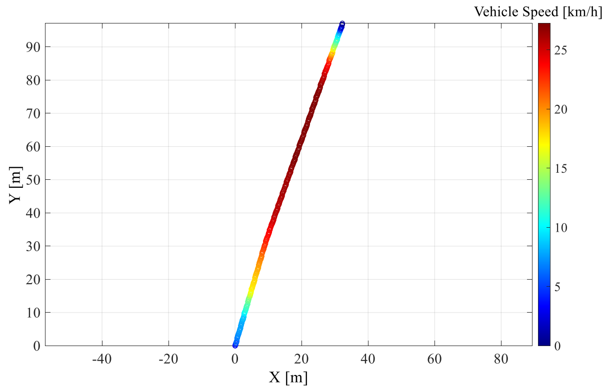

Figure 4: Example of GPS acquisition during a maneuver with a 70% constant accelerator pedal followed by a 70% constant brake pedal

The subplot of pickup speeds shows how their measurements are reliable when compared against the vehicle speed measured by the IMU, thus proving the efficacy of the custom mounting support even in presence of high vehicle vibration levels. Furthermore, the wire transducers compression measurement well describes the road wheel displacements, in agreement with the longitudinal acceleration and pitch angle elaborated from the IMU.

The GPS installed together with IMU can also provide useful information in terms of vehicle trajectory, as also reported in Figure 4.

IV. VEHICLE DYNAMICS MODEL VALIDATION

The multibody model of track vehicle dynamics is carried out in the ADAMS ATV environment. It is possible to define the dimensional and mechanical characteristics of the constituent parts of a track assembly: rubber pads of track assemblies, pins, connecting elements, suspension system with torsional bars, dampers and bump stops, etc., as well as the sprocket and track road wheels.

An important feature of the model is the possibility of acting on the track tension, an adjustment parameter that has an important influence on the dynamic behavior of the vehicle.

The software allows to test the vehicle in different environments, hence in both hard (asphalt or concrete) and soft soils of different characteristics such as clay, dry or wet soil, snow, sand, etc.. In addition to this, it is possible to generate test tracks of any morphological characteristics. This feature makes it possible, once the model has been experimentally validated, to predict the dynamic behavior of the vehicle in even very different terrain conditions. The multibody model of the vehicle is shown in **Errore. L'origine riferimento non è stata trovata.**.

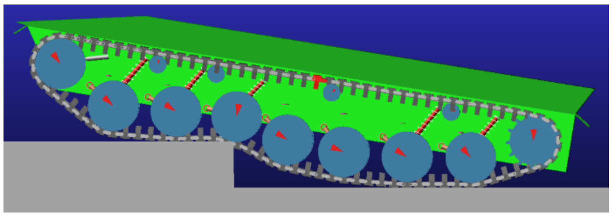

Figure 5: Tracked vehicle multibody model passing over a stepped obstacle.

The following procedure is defined in order to obtain a reliable and experimentally validated simulation environment for tracked vehicle dynamics assessment:

1. Create in ADAMS ATV the road profile required to replicate the experimental maneuvers. This step only occurs when a road irregularity is present during the maneuver, i.e. over stepped obstacles or longitudinal and transverse sloped roads;
2. Export the angular speed time histories for the two sprocket wheels from experimental measurements. The filtered measurements are furtherly processed to extrapolate only the relevant part of the maneuver and undersampled to reduce the computational cost for simulating the maneuver. The sampling time selected is 100 Hz;
3. Run the simulation with ADAMS ATV and save the quantities needed for the validation of that specific maneuver;
4. Make the comparison between the simulated results and the experimental measurements through a dedicated script elaborated in Matlab® environment;

5. In case of mismatch between experiments and numerical results, the uncertain parameters of the ADAMS ATV model are updated to achieve a closer behavior to the actual vehicle. The selection of the right parameters to be modified is based on the maneuver executed, i.e. longitudinal or cornering, with or without road irregularities, etc…, and on which quantities mostly differ from their corresponding experimental measurements.

The following considerations explain the small differences revealed by comparing model with experimental measurements:

- The proving ground presents both lateral and longitudinal slopes, which are modest but not zero and not known quantitatively. Therefore, some deviations between the model and experiments are expected in terms of lateral and longitudinal accelerations, pitch and roll angles. These deviations are considered acceptable because, being small, they do not have a significant impact on the vehicle dynamic behavior.
- The IMU acceleration measurements are affected by the acceleration of gravity, while the corresponding simulated quantities only evaluate the dynamic contributions. To compensate for this difference, the contribution due to the acceleration of gravity has been removed from the experimental data, by considering the vehicle roll and pitch motion. However, due to the uncertainties in the proving ground longitudinal and lateral slopes, the influence of the acceleration of gravity cannot be completely eliminated;
- Due to the position of the wire transducers magnetic support, which is constrained by the available space under the hull, and to the other wire end attached to a different point from the wheel center, an accurate suspension kinematics is required to evaluate and compare each road wheel vertical travel. Uncertainty related to the position and orientation of the transducers with respect to the suspension system could also produce differences between numerical and experimental results.

An example of the output of the validation procedure is reported in Figure 6.

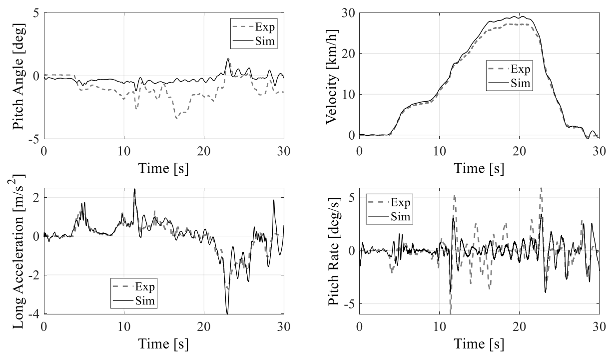

Figure 6: Example of the validation procedure during a maneuver with a 70% constant accelerator pedal followed by a 70% constant brake pedal

The figure shows the comparison of the pitch angle, the longitudinal speed, the longitudinal acceleration and the pitch rate during the experimental maneuver executed in Figure 3 and Figure 4. The vehicle longitudinal acceleration and speed are well represented by the vehicle model, while some discrepancies are visible in the pitch dynamics, which may be justified by the uncertainty of the road slope, which is currently not modelled in the multibody simulation.

V. CONCLUSIONS

Preliminary validation outcomes have demonstrated that the experimental methodology currently adopted is both effective and robust. It enables the acquisition of several kinematic and dynamic mechanical quantities that are essential for validating the vehicle multibody model at different operating conditions. The validation yielded promising results regarding the ability of the multibody model to accurately represent the actual dynamic behavior of the tracked vehicle.

As future developments, there are plans to broaden the methodology to include acceleration measurements at the driver's seat to assess ride comfort quality, as well as to evaluate through NVH measurements, the durability of on-board electrical and electronic systems, which are especially exposed to heavy vibrations while driving on uneven terrains.

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