APPLICATION

System engineering design approach and virtual assessment of a new charging arm concept for LHC robotic TIM

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Abstract

System engineering (SE) methods and principles are nowadays widely adopted in the product development processes, especially in the industrial sector, where saving production time and costs are primary goals. This work describes an application of a particular SE methodology, the V-model-based design, in which the system development lifecycle is divided on the basis of a graphical V-shaped scheme, called V-model. Following this approach, a new concept of charging arm for Robotic Train Inspection Monorail (TIM) of Large Hadron Collider (LHC) at CERN (Conseil Européen pour la Recherche Nucléaire) has been developed. The current charging arm version is affected by several issues and limits that have led to the necessity of a new solution. Starting from the first stages of functional requirements (FRs) definition and decomposition (left side of the "V"), a new concept has been implemented, in order to be tested for its verification and validation (right side of the "V"). As part of the principles of SE, the process has been based on virtual models of the product and on virtual simulations of its operation, rather than on the realization of time-consuming and expensive physical models and tests, even if a final physical prototype has also been built and some physical operative tests have also been carried out on it. These tests have showed that the new product appears to fulfill each one of its FRs and overcome the limits imposed by the previous version. The future commissioning and operative tests in the real operating condition and location shall definitely validate the new product.

Keywords System engineering · V-model-based design · Additive manufacturing · Design for manufacturing · Finite element method · Virtual reality

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1 Introduction

The Large Hadron Collider (LHC) is the largest particle accelerator in the world, designed and developed at CERN (Conseil Européen pour la Recherche Nucléaire) with the aim of pushing the research on the particle physics to the limit. It is placed in a tunnel located 100 m underground and covering a circumference of 27 km. The accelerator and its surroundings need to be inspected and monitored remotely, due to the presence of human hazards mainly produced by radiation and high magnetic fields. Train Inspection Monorail (TIM) [1] fulfills this task; it is a robot travelling on a monorail, suspended from the ceiling of the LHC's tunnel, parallel to the accelerator (Fig. 1).
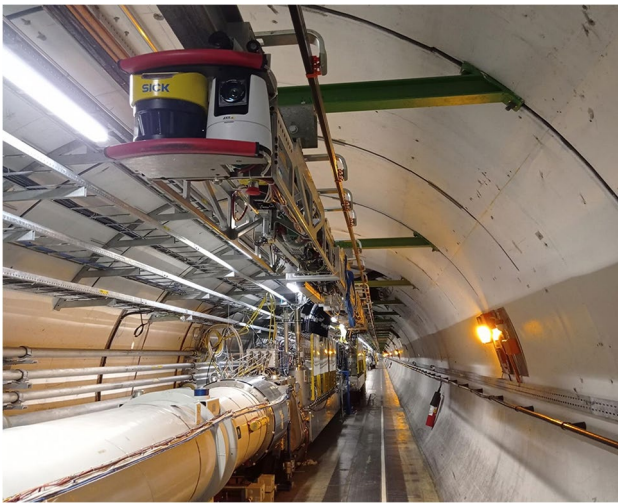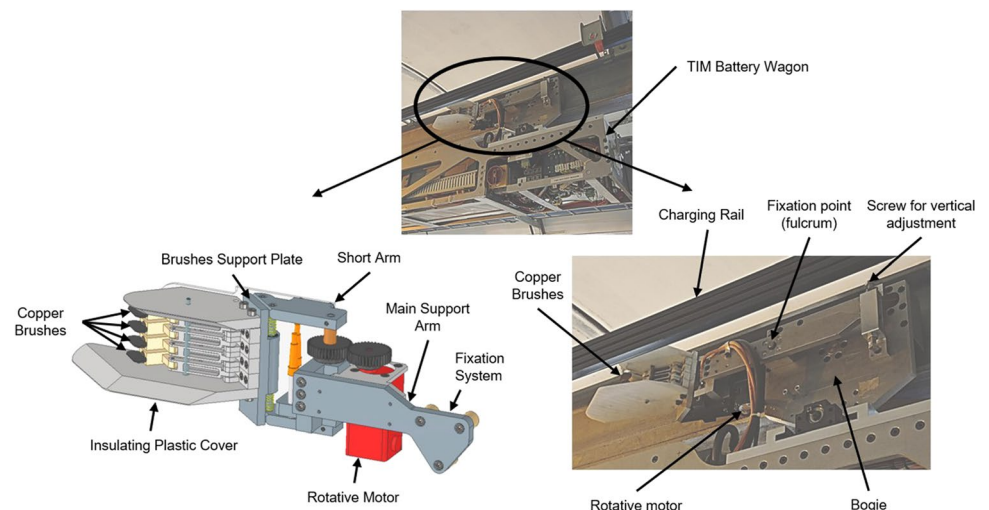

Fig. 1 Train Inspection Monorail (TIM) in the Large Hadron Collider (LHC) tunnel

TIM carries out both autonomous and remote-controlled operations and is electrically fed by a 24 Volts battery placed on one of the five wagons that make up the train, called battery wagon for this reason. The charge of the battery is ensured by an aluminum-made robotic arm, called charging arm (CA), which is also remote-operated to insert four copper-made current collector brushes (CCBs) in four conductive rail channels (CRCs) of a charging rail (CR) parallel to the TIM's monorail. The activation of CA can be autonomous if the batteries are low and the train stands still. CA is placed on the surface of the bogie, which is the sub-system of TIM that hosts the wheels and whose surfaces, therefore, are always parallel to the monorail and to the CR. In the present version, CA is a 2 DoFs system, as it needs to be opened and closed, respectively to approach the CR in the charge-on operation and to come back in its rest position in the charge-off one, and vertically adjusted to adapt to the CR's variable height. The first DoF is actuated by an electric rotative motor remotely operable, while the second one is currently enabled by manually acting on a screw placed on one CA's end, which rotates the arm around its central fixation point so as to move vertically the other end, where the CCBs are mounted. The current charging arm configuration is shown in the following Fig. 2.

The possibility to adjust CA's height only manually and not in a remote-controlled way is one of the limits of the present version. However, the most important issue of the current CA's version is the frequent lack of insertion of the CCBs inside the CRCs, which prevents or slows down the correct charge of TIM. This situation is due to the presence of imperfections on the CR, which, not being designed to be accurate along its entire 27 km length in the LHC tunnel, make the relative distance between the CRCs not always equal to the nominal one. An example is shown in the following Fig. 3.

Fig. 2 Present version of charging arm (CA) and its features

Fig. 3 Example of a manufacturing inaccuracy on the charging rail (CR): the vertical distance between the different Conductor Rail Channels (CRCs) is not the same

(a) *Outside view*   (b) *Internal view*

Since it is obviously difficult, time consuming and expensive to carry out maintenance operations on the CR to correct its defects all along its path, a more elastic version of charging arm is required, able to adapt to this situation and charge TIM even in presence of CR's imperfections. Moreover, other limits of the present CA's version lie in the possibility to charge TIM only at standstill and not during its run, due to problems of sparks and excessive friction, and in the absence of a position sensor to monitor the opening level of the arm instant by instant.

The aim of this paper is to show the design and development of a new charging arm concept able to overcome the limits of the present version. The development process of the product has been carried out following the principles of system engineering (SE) and V-model-based design, with a well-defined subdivision of the different stages and a strong communication between each of them. Therefore, starting from the definition and decomposition of the FRs, the best concept has been chosen among several alternatives and developed, to be finally tested through different types of virtual and physical simulations, aimed at achieving the verification and validation process.

2 Methods: system engineering approach and V-model-based design

The design and development of a new concept for charging arm have been carried out using SE methods and tools. SE finds its origins in the field of industrial production to save time and money by giving principles, methods, and tools capable of reducing the risks of developing a non-conform system and ensuring the quality of the final product. The ideas of SE are founded on a clear demarcation of the product development process' stages and on their constant communication, in order to guarantee the efficiency of the process itself and overcome the weaknesses of a trial-and-error approach [2]. Among the several SE methodologies, the model-based system engineering (MBSE) [3] is one of the most implemented; instead of using document-based information interchange as its primary method, it focuses on developing and utilizing domain models [4, 5]. In this case, the domain model used to define the product development process and its different stages is the V-model. It is a V-shaped graphical representation of the product

development lifecycle which divides the workflow into two streams: the specification stream, on the left side of the "V," featuring the definition and decomposition of requirements and the system design, and the testing stream, on the right side of the "V," featuring the integration, verification, and validation of the system. Correspondent steps of the V-model are connected to trace requirements and keep communication [6, 7]. In this case, each side of the V-model has been divided into four stages, with a middle transitional stage of Implementation of the design (Fig. 4).

2.1 Specification stream: definition, decomposition, and design

2.1.1 High-level requirements and constraints analysis stage

The drafting of a list of functional requirements (FRs) and a well-conducted analysis of the constraints the product needs to respect represent the foundations for a correct execution of the next process stages. In this application, high-level FRs have firstly been analyzed; they are directly derived from the limits of the present CA's version. Then, they have been formalized and decomposed into three hierarchical levels, as shown in Table 1.

As regards the constraints, they are principally dimensional constraints since:

- CA needs to be placed on the Bogie's surface, as this is the only one to be always parallel to the CR (Fig. 5a)
- CA needs to allow Bogie's opening in case of maintenance operation. In fact, when TIM needs to be dismounted from the monorail and put down, the bogie is opened, and its surfaces are separated from the monorail, getting closer to the CR. This means that the available space for CA in its closed configuration reduces up to a value of 70 mm, as shown in Fig. 5b
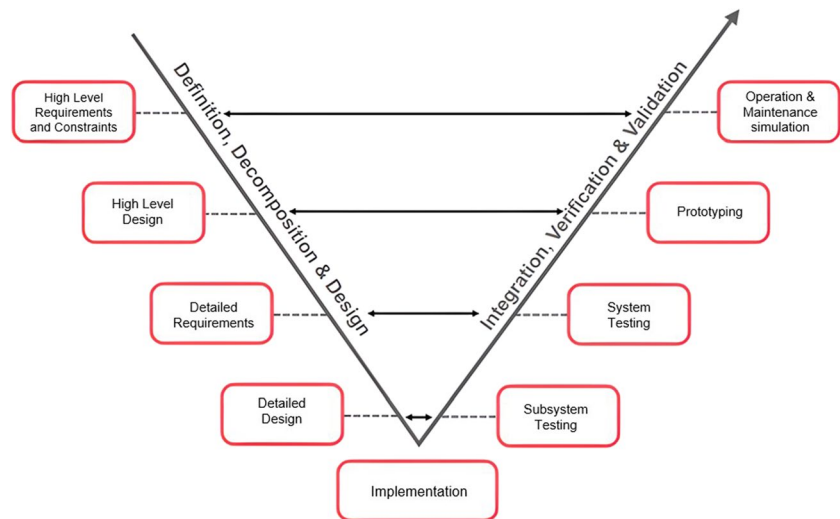
Fig. 4 V-model-based design

Table 1 High-level functional requirements (FRs)

Level 1	Level 2	Level 3	Functional requirement
FR 1			Charging arm (CA) shall charge TIM
	FR 1.1		CA shall be remotely opened and closed
	FR 1.2		CA shall be remotely adjusted in height (± 1 cm)
	FR 1.3		The current collector brushes (CCBs) shall insert correctly in the Conductor Rail Channels (CRCs)
		FR 1.3.1	CA shall be elastic to adapt to the defects of the charging rail (CR) and manage to insert the CCBs in the CRCs
	FR 1.4		CA shall withstand all applied loads
		FR 1.4.1	CA shall withstand resting loads
		FR 1.4.2	CA shall withstand operative loads

Fig. 5 Dimensional constraints
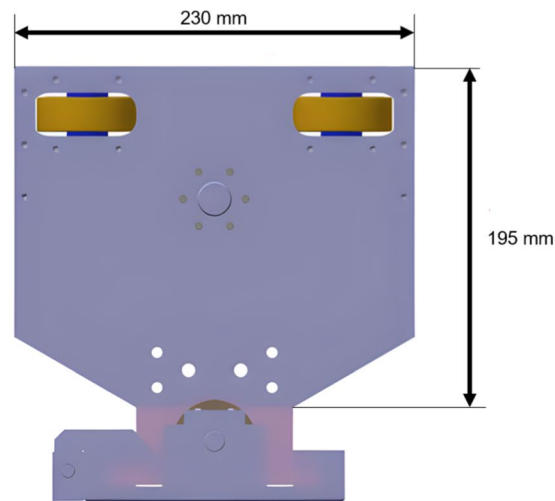
(a) *Dimension of the Bogie's surface on which CA needs to be placed*
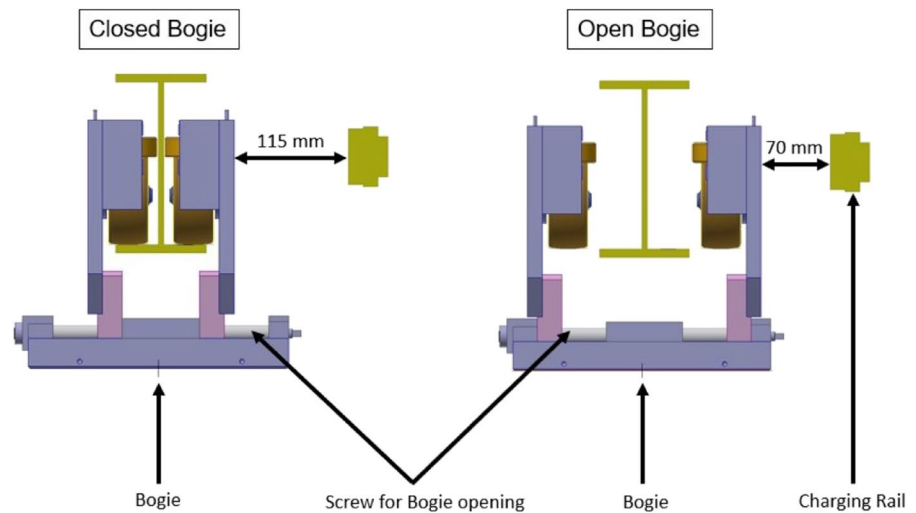
(b) *Reduction of the available space for CA in case of Train Inspection Monorail (TIM) removal for maintenance operations*

2.1.2 High-level design stage

The high-level FRs and the constraints act as input for the next stage of high-level design, also called concept design, in which the aim is to produce as many ideas, sketches, and solutions as possible.

This stage has been inspired by a patent analysis, in which patents of several types of mechanisms have been analyzed. In particular, pantograph mechanisms for charging of transport systems, like trains, trams, and electric buses, have been interesting sources of inspiration (Fig. 6), even if simpler mechanisms, for instance, the car scissor lift, have also been analyzed [8–11]. The major concern regarding these systems is the need to fit in the reduced available space for charging arm.

The first sketches both on paper and in virtual environment, exploiting the 3D CAD software Autodesk Inventor, have been developed. Two of them are shown in Fig. 7.

Common characteristics of the different preliminary CA's concepts are as follows:

- Presence of the same CCBs used in the present CA's version, in order to start the mechanical design taking into account the encumbrance of the real system.
- Presence of a multilink system moved by a remote-controlled screw drive motor for the opening DoF.
- Presence of a system of springs to support the CCBs, in order to enhance the elasticity of the system required to adapt to the CR's imperfections.
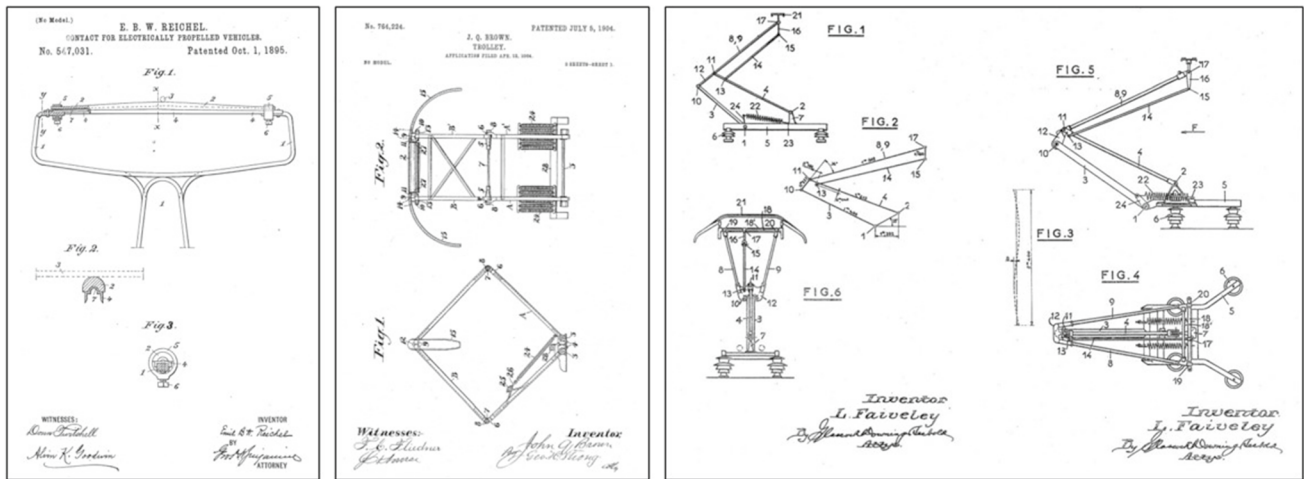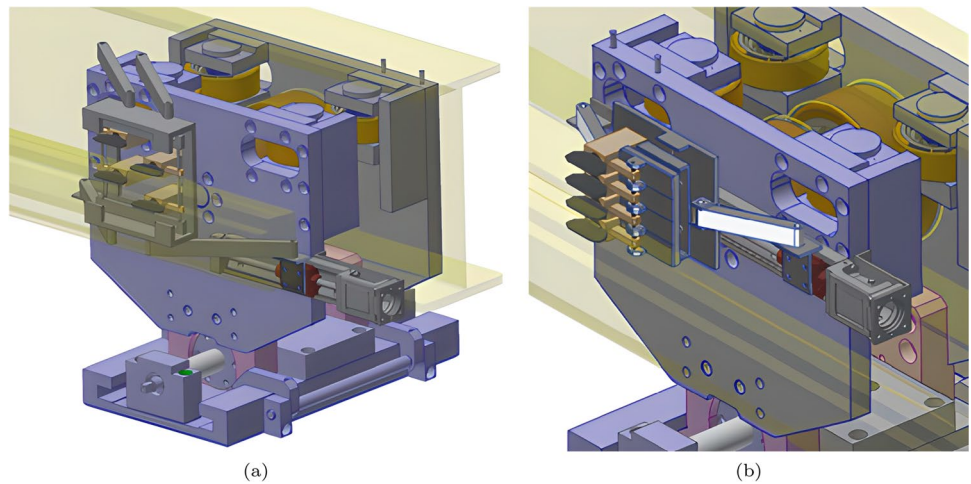
Fig. 6 Patents of first pantograph mechanisms for transport systems charging [8–10]

Fig. 7 Two examples of the concepts developed in the high-level design stage

(a)   (b)

Even if these concepts have provided ideas and solutions adopted in the following stages, some limits have been highlighted when a second analysis of tighter detailed functional requirements has been carried out.

2.1.3 Detailed requirements analysis and detailed design stages

The analysis of the preliminary designed concepts has led to think about new and more detailed FRs, not yet addressed, principally regarding the number and position of the driving motors and the need of charging during TIM's run.

The updated and complete list of FRs, decomposed into four levels, is represented in Table 2.

These requirements have led in turn to a new stage of more detailed design, in which new 3D sketches have been developed.

In this stage, a benchmark analysis has also been carried out, searching and comparing similar products usually adopted for industrial bus-bar systems and overhead cranes. The analysis has allowed to find interesting commercial current collectors (CCs), characterized by compactness, elasticity, and capability to work during the run (Fig. 8). In fact, they are designed through dedicated materials and elastic structures able to guarantee a correct operation and charging also during train's run: elasticity ensures correct insertion and permanent contact between CCBs and CRCs, providing adaptability to the path of the charging rail, to different contact pressures and to the variable position of the CRCs; dedicated materials and proper brushes' shaping avoid problems of friction. Hence, this helps to fulfill FR 1.3 and new FR 1.5 (and the respective lower-level ones). Another inspiring solution coming from the benchmark analysis has been represented by CCs made of two different groups of brushes, placed symmetrically (showed on the right side of Fig. 8). Since the brushes of just one side need to fit in the CRCs to ensure the correct charge, this configuration allows to halve the probability of charge failure; moreover, the two sides

Table 2 Complete list of functional requirements, updated with more detailed ones

Level 1	Level 2	Level 3	Level 4	Functional Requirement
FR 1				Charging Arm (CA) shall charge TIM
	FR 1.1			CA shall be remotely opened and closed
		FR 1.1.1		The driving motors shall be fixed and placed on the Bogie's surface
			FR 1.1.1.1	The driving motors shall be placed in an accessible position to be manually unlocked in case of locking
		FR 1.1.2		CA's opening/closing movement shall be guaranteed even in case of one motor's locking/break
	FR 1.2			CA shall be remotely adjusted in height (± 1 cm)
	FR 1.3			The current collector brushes (CCBs) shall insert correctly in the Conductor Rail Channels (CRCs)
		FR 1.3.1		CA shall be elastic to adapt to the defects of the charging rail (CR) and manage to insert the CCBs in the CRCs
	FR 1.4			CA shall withstand all applied loads
		FR 1.4.1		CA shall withstand resting loads
		FR 1.4.2		CA shall withstand operative loads
	FR 1.5			CA shall operate during TIM's motion (up to a speed of 6 km/h)
		FR 1.5.1		The sliding contact between CA and the CR shall not cause over-friction or spikes troubles
			FR 1.5.1.1	CA shall adapt to the different positions of the CR in order to keep the contact between the CCB and the CRC stable
			FR 1.5.1.2	CCB's material shall not prevent the sliding contact

Fig. 8 Some commercial current collectors analyzed. Single-side CCs are displayed on the left, while double-side symmetric CCs are on the right
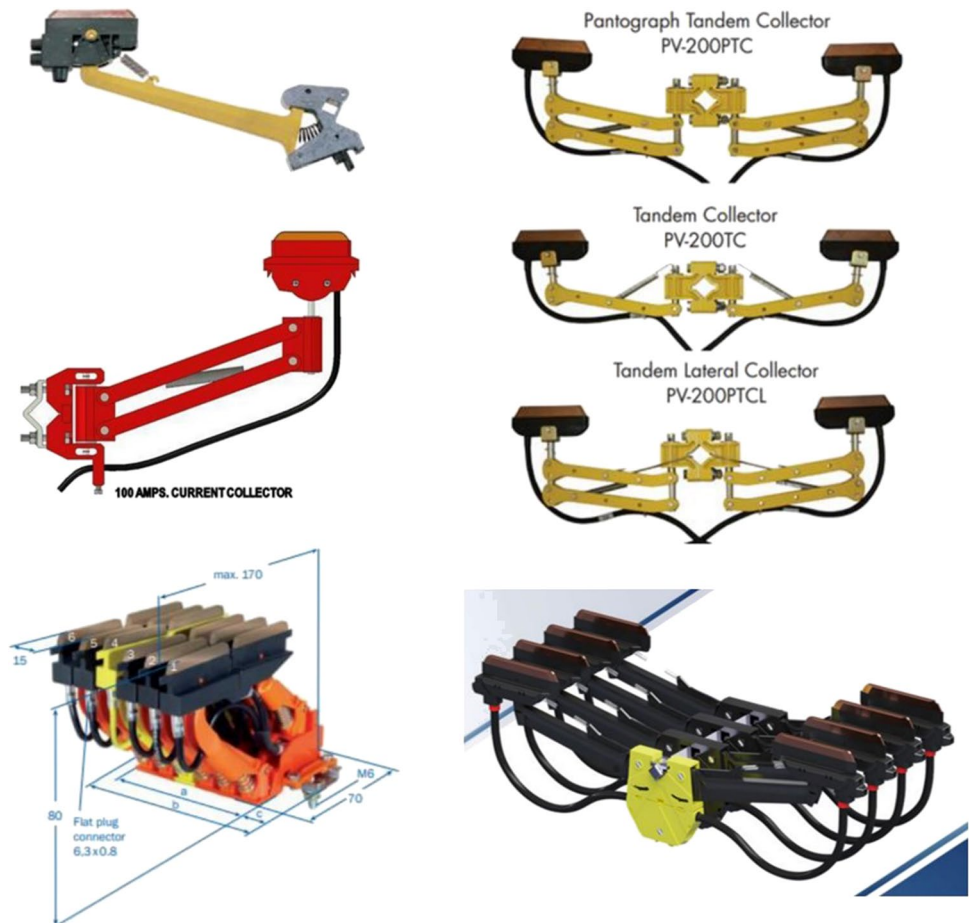
are elastically connected by the central body, so that if one side approaching the CR is subject to a stronger repulsion force (as in the case it cannot enter in the CRCs), it transfers the load to the other side, which is pushed more on the CR and is more likely to correctly fit in the CRCs and ensure the charging.

However, this kind of product has too large dimensions with respect to the available space, therefore a single-sided CC has been purchased (Fig. 9a). It has been selected from the catalog of the charging rail manufacturer, to ensure proper compatibility, as the smallest four-pole version, since TIM Charging Rail provides four conductive channels. In addition to compactness, elasticity, and capability to operate during motion, it is characterized by a high number of DoFs, as shown in Fig. 9b, which allow it to adapt to the tortuous path of the charging rail and to the variability of the CRCs' position:

- Rotation of each arm about the z-axis
- $\pm 20°$ rotation of each brush about the x-axis
- ± 15 mm translation of each brush along the z-axis, thanks to the rotation of each arm about the x-axis, controlled by the internal spring

The capability of this product, as well as of all the analyzed ones, to work during motion also represents their drawback, since they are designed to be always in contact with the rail and therefore are not provided of an actuation mechanism. In fact, the purchased CC represents only a sub-system of the whole TIM charging arm, which instead shall comprise also the mechanism (actuators and kinematic chain) to move it and activate charging when required. Therefore, all the efforts made in the next stage of detailed design have been focused on the integration of the purchased CC in the whole charging arm and on the design of its actuation mechanism.

New concepts have been developed also to fit the newly arisen requirements. In some of them, the previously shown commercial products provided with a doubled, symmetric configuration of brushes have been replicated positioning two instances of the purchased CC symmetrically, in order to employ their advantages. Two of the several concepts developed including the purchased CC are shown in Fig. 10. Some innovative features destined to be part of the final best concept are the linear screw drive motors for actuation and the support plates with z-shape for encumbrance reduction.

2.2 Choice and implementation of the best concept

Several sessions of team brainstorming have been conducted to develop and optimize the designed concepts in order to obtain a unique best concept to be implemented. It is shown in Fig. 11.

It is characterized by specific features:
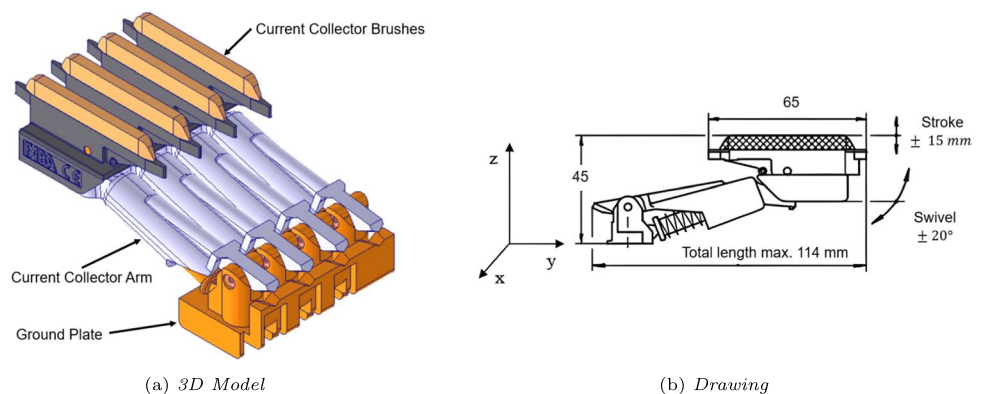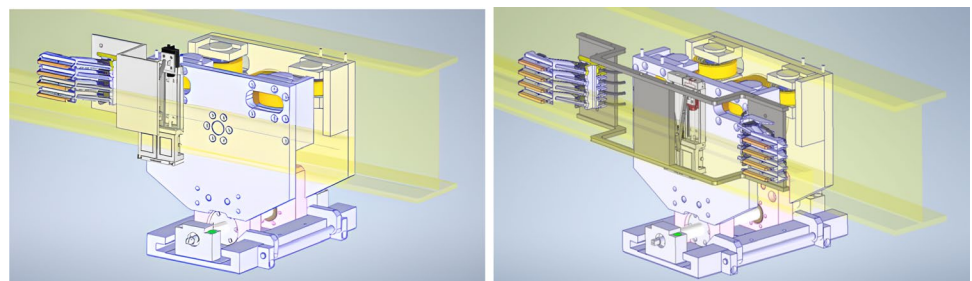
Fig. 9 Purchased current collector (CC)

(a) *3D Model*

(b) *Drawing*

Fig. 10 Two of the new concepts developed in the detailed design stage

(a) *The purchased CC is implemented in the 3D environment and used as dimensional input for the sizing of the mechanism*

(b) *Two units of the purchased CC are placed on a symmetric mechanism inspired by the benchmark analysis*

Fig. 11 Best concept and its characterizing features
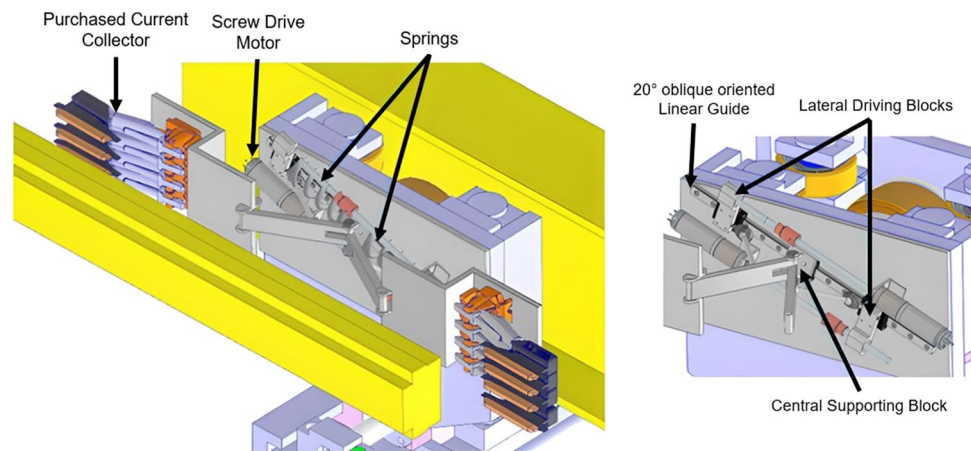
- Three blocks sliding on an oblique-oriented linear guide, two of which are lateral driving blocks (LDBs), moved by a screw drive motor each, and one is a central block (CB), supporting the whole system and connected to the lateral ones by means of springs. The oblique orientation allows to remotely move the system both horizontally and vertically through the same two motors and to easily access the motors manually from the side in case of locking. Moreover, the oblique direction, clearly longer than the vertical and horizontal ones, enhance the space available for the screw drive motors, guaranteeing to complete LDBs' required stroke for charging arm opening while keeping the motors fixed on bogie's surface. Therefore, this configuration allows for the fulfillment of FR 1.1, FR 1.1.1, FR 1.1.1.1, and FR 1.2.
- A central main structure burden on the CB is made of two support links, one for each side, each one moved by a driving link, in turn, connected by spherical joints to the LDBs. Spherical joints are needed to couple the translation of the LDBs in the oblique direction to the rotation of the support links in the horizontal plane.
- Two models of the purchased CC were placed symmetrically on aluminum-made plates designed with a Z-shape in order to reduce the system's encumbrance. Since just one CC shall insert its four brushes into the CRCs to ensure the success of charge-on procedure, doubling the CCs allows to halve the probability of procedure fail due to coupling issues (this means doubling the probability to fulfill FR 1.3).

The springs connecting the CB to the LDBs allow the following:

- Remotely move the system vertically through the concordant translation of the LDBs, keeping the CB in the middle and the whole system symmetric (FR 1.2).

- Open/close the system through the discordant translation of the LDBs, keeping the CB in the middle and the whole system symmetric (FR 1.1).
- Ensure the opening/closing movement even in case of one motor's locking, moving the other motor and, in this way, obtaining the desired redundancy (FR 1.1.2).
- Transfer force between the two CCs in case one of them faces an imperfection on the CR and its brushes cannot insert; in fact, the spring system allows to transform the repulsion force on one CC in a pushing force on the other CC. Hence, the presence of two CCs placed symmetrically and elastically connected to each other allows for an automatic mechanical self-compensation of errors during the insertion of CCBs in CRCs, increasing the capability to adapt to CR defects (FR 1.3 and FR 1.3.1 more likely to be satisfied). This also provides aid to ensure constant contact, and therefore charging, in case of charging during TIM's motion (FR 1.5).

The best concept appears to fulfill each FR. With respect to the previous charging arm version, the newly developed one provides more reliability both against charge-on procedure failure due to insertion errors, thanks to the CCs doubling and the elastic errors' self-compensation, and against motors failure, thanks to their doubling and their positioning favorable for manual maintenance. The kinematics of the mechanism allows for a remotely operated vertical translation of the system to adapt to possible different CR heights, which in the previous version should instead be performed manually. Finally, the implementation of commercial CCs designed to operate also during running allows for the development of the procedure of charging in motion, which would avoid to require stop of train operation for charging. In general, even if this solution can appear quite complex and difficult to implement in such small spaces without compromising its robustness, it however appears feasible, efficient, and reliable, even against rescue scenarios. Therefore, it has been

developed and implemented, following a design for manufacturing (DFM) approach, thus respecting the principles of modularity, standardization, simplification, and parts optimization [12, 13]. A few specific adjustments have been made to guarantee product strength and compactness. The sizing of the driveline, in each of its links, has been carried out through a preliminary kinematic and dynamic calculation, in which the required closed (charge-off) and opened (charge-on) positions of the CCs have been inserted as inputs, and the lengths of the links have been varied to obtain the optimum configuration able to minimize:

- The stroke required to the lateral driving blocks (s) to completely open the mechanism
- The force required to the screw drive motors (F_d) to push the CCs against the CR until the opening is completed and all the brushes are correctly inserted in the CRCs. This parameter has also led to the preliminary sizing of the screw drive motors to be purchased

The final configuration of CA is shown in the following Fig. 12. Some parts, like the support plates and the moving links, are planned to be CNC-machined at CERN in aluminum 6061, while the others, like the linear guides, the spherical joints, pins, screws, and nuts, are planned to be purchased on the market and made of stainless steel.

3 Testing stream of the V-model: virtual and physical simulations and results

The implementation of the best concept represents the transition phase between the specification stream of the left side of the "V" and the testing stream of the right side of the "V." The different testing stages have been performed through a series of simulations exploiting different platforms, with the aim of verifying and validating each functional requirement.

3.1 Dynamic virtual simulation and subsystem testing

The testing process has started with the operative validation of the designed mechanism. This has been carried out by performing a number of dynamic simulations over the dynamic simulation environment of Autodesk Inventor, allowing for a preliminary verification of the capability of each feature to address the requirements for which it was conceived. The simulation session has been divided into four test cases:

- Test Case 01_01: simulation of opening and closing movement (respectively charge-on and charge-off procedures).
- Test Case 01_02: simulation of vertical movement (height adjustment procedure).
- Test Case 01_03: simulation of motor failure, i.e., simulation of charge-on/off and height adjustment procedures with single motor actuation.
- Test Case 01_04: simulation of CCBs insertion in CRCs in case of misalignment/interference (simulated through an amplified contact force on one CC only).

Each test case has showed good results, proving that the new charging arm can correctly be opened, closed, and vertically adjusted, even in case of one motor failure, as well as correctly insert the CCBs in the CRCs self-compensating possible misalignment and interference. This has been assessed in terms of both kinematic behavior and dynamic behavior. In fact, each subsystem, in particular those purchased on the market, has been verified against the applied
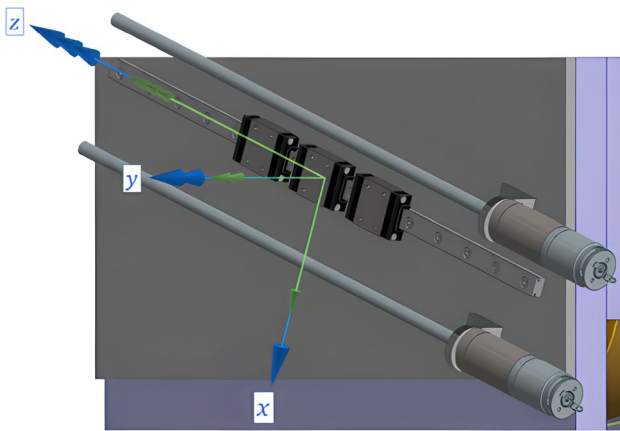
Fig. 12 Final configuration of charging arm
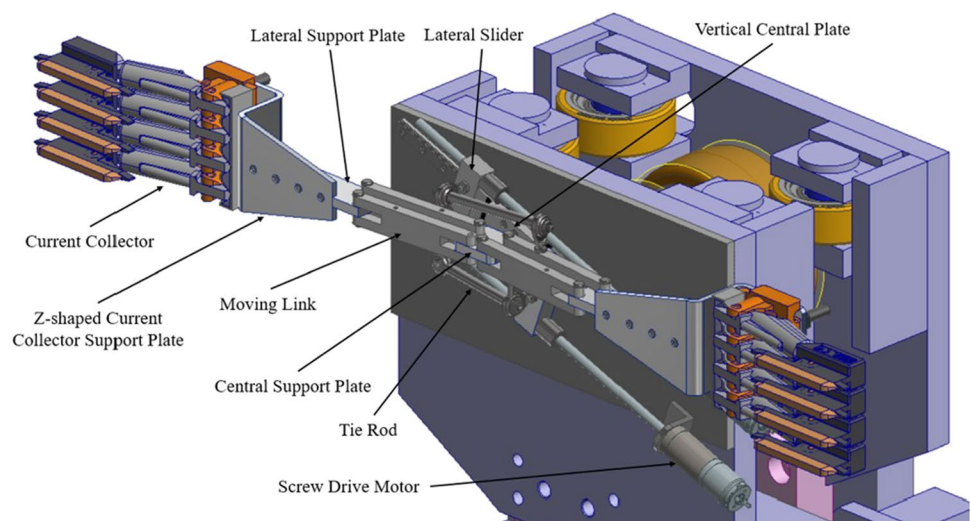
Fig. 13 The critical load is the torque acting on the central block (CB) about the *Y*-axis of its coordinate system

loads (mainly weight force, elastic force, and maximum contact force with charging rail). The forces applied on each sub-system in each direction have been evaluated as output and compared to the limits imposed by the manufacturers, giving positive results. No component has resulted to be over-loaded: the most loaded one is the CB, whose maximum applied load (torque about the *Y*-axis of its coordinate system, shown in Fig. 13) is however under the limit with a safety factor of the following:

$$n = \frac{M_y, a}{M_y, max} = 1.25 \qquad (1)$$

The dynamic simulations have also allowed to definitely size the screw drive motors, in order to guarantee correct operation with enough safety margins under each test case.

To provide an example, the input parameters implemented in Test Case 01_01 simulation regarding the most common procedure of opening/closing (charge-on/charge-off) are described:

- A trapezoidal LDBs' velocity profile, such to complete the opening operation in the same time as the previous CA's version, that is 6 s, with motor's start-up and stopping time assumed equal to 0.5 s, given the stroke required to the LDBs *s*:

$$v = \frac{s}{t} = \frac{17.6}{6} \frac{mm}{s} \qquad (2)$$

- A linear behavior of the contact force applied on each CCB due to the pressure against the CRC, in the function of the CCB position, such to simulate the actual elastic behavior of each current collector arm (CCA). The maximum value of the contact force, reached in the most opened configuration, has been supposed equal to

the maximum applicable load on each CCA of 6 N (prescribed by the manufacturer), to consider the worst loading condition. An equivalent system of only two forces for each side instead of four has been considered for simplicity (Fig. 14).

- Joints friction coefficients depending on the materials in contact, in order to consider all the real frictions in the driveline.

Further virtual simulations will be done to assess the kinematic and dynamic behavior of charging arm while running on the charging rail, testing possible variation of contact force or even possible presence of vertical force due to CR shape variation. However, the actual fulfillment of the requirements can only be confirmed through a physical test session with prototypes (see next Sect. 3.4).

3.2 System testing and structural assessment through finite element method (FEM)

After the verification of the purchased subsystem achieved through the dynamic simulations, the whole system has been structurally verified through finite element analyses (FEA), paying particular attention to those components built in-house at CERN. This allows to validate FR 1.4.

In particular, two different analyses have been carried out:

- Test Case 02_01: analysis on the critical threaded connections between the CB and the aluminum-made plates that sustain the central system (shown in Fig. 15), under the weight force of the system. The aim is to verify that only two M2 screws can sustain the whole central system. Since resting loads only include the system's own
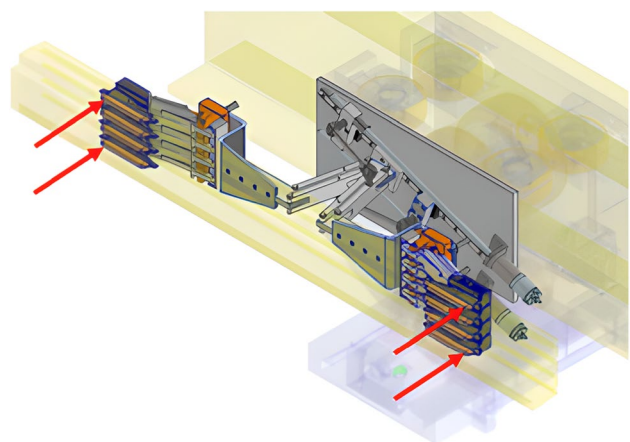

Fig. 14 An equivalent system of two forces for each side has been considered, instead of the real four forces, one for each current collector brush (CCB)

weight, positive result of this assessment will lead to a preliminary validation of FR 1.4.1

- Test Case 0202: analysis on the central mechanism (shown in Fig. 16) under operational loads, which are system's own weight force and contact pressure against CR. This has been conservatively considered as the maximum applicable contact force on the CCs prescribed by the manufacturer (6 N for each CCB). The aim is to validate FR 1.4.2 and demonstrate CA can withstand operative loads, and therefore all applied loads (FR 1.4). The CCs have been simulated as points of mass acting on the support plate holes. The target is to keep the horizontal displacements of the support plates under the value of 3 mm, that is the distance between them and the CR in operating position (Fig. 17), so as to avoid their impact

Both the analyses have been conducted through the typical steps of a finite element analysis, thus with three different main stages:

a) Preprocessing, furtherly divided into the following substeps:

- Geometry import and clean-up
- Materials assignment
- Contacts assignment
- Mesh generation: high-quality mesh with SOLID186 hexahedral elements (Fig. 16)
- Loads and constraints assignment

b) Processing: non-linear iterative calculation, due to the presence of non-linear contacts

c) Post-processing and results analysis

The results have been positive in both cases:

Fig. 15 Critical threaded connections, structurally verified in the first finite element analysis
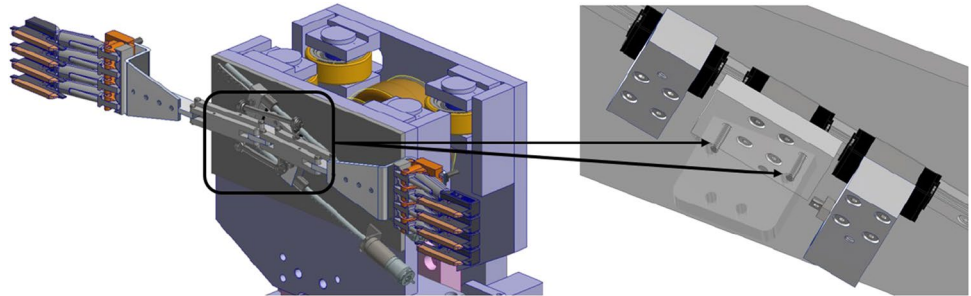
Fig. 16 Central system structurally verified in the second finite element analysis. A high-quality mesh with SOLID186 hexahedral elements has been generated
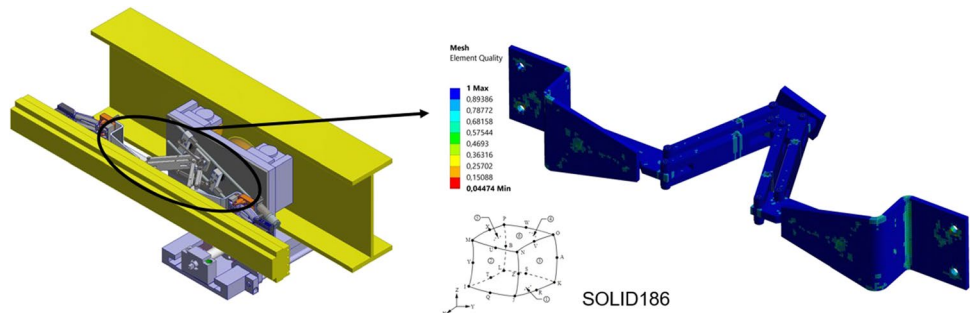
Fig. 17 Operative nominal distance between the metal supporting structure and the CR. It represents the maximum allowable deformation of the supporting structure due to the contact pressure between the CCs and the CR such to avoid its impact on the CR
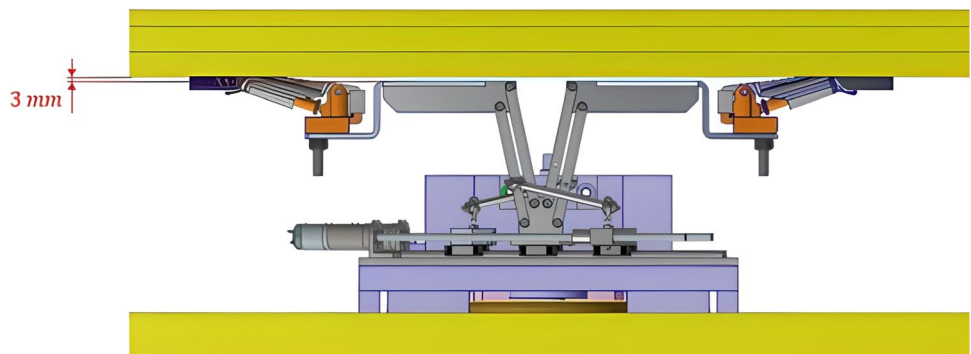
Fig. 18 Equivalent Von Mises stress distribution on the critical threaded connections sustaining the system
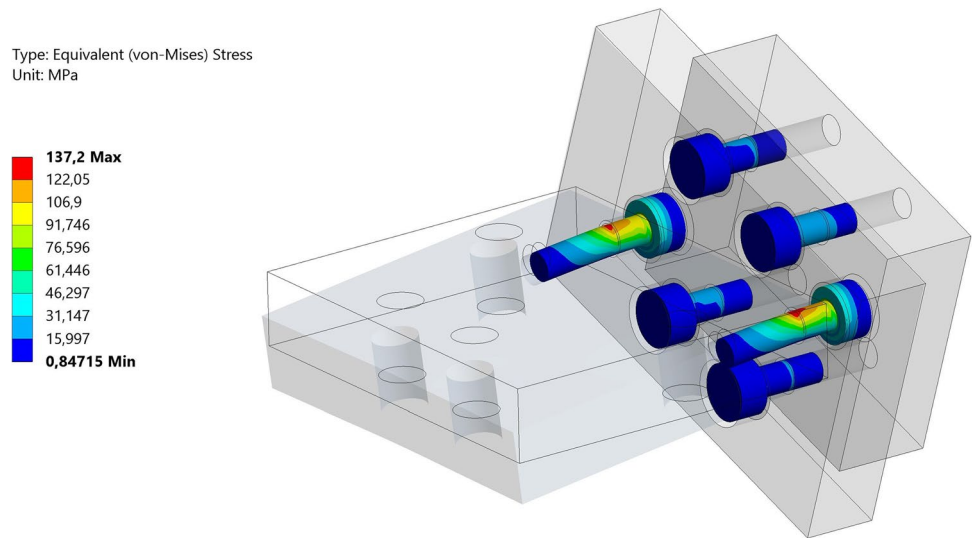
1. In the first analysis, the contour plot of the equivalent Von Mises stress distribution on the screws (Fig. 18) shows a maximum value of 137.2 MPa, with a safety factor with respect to the screws' stainless steel yield strength (450 MPa) of

$$n = \frac{\sigma_y}{\sigma_m ax} = \frac{450}{137.2} \frac{MPa}{MPa} = 3.28 \quad (3)$$

This means that only two M2 screws are enough to sustain the whole central system.

6. The second analysis has showed the effects on the central mechanism of the weight force of the system itself and of the contact force between the CCs and the CR. The contour plot of the horizontal displacement distribution in Fig. 19a shows that the bending of the

Fig. 19 Results of the second finite element analysis on the central system
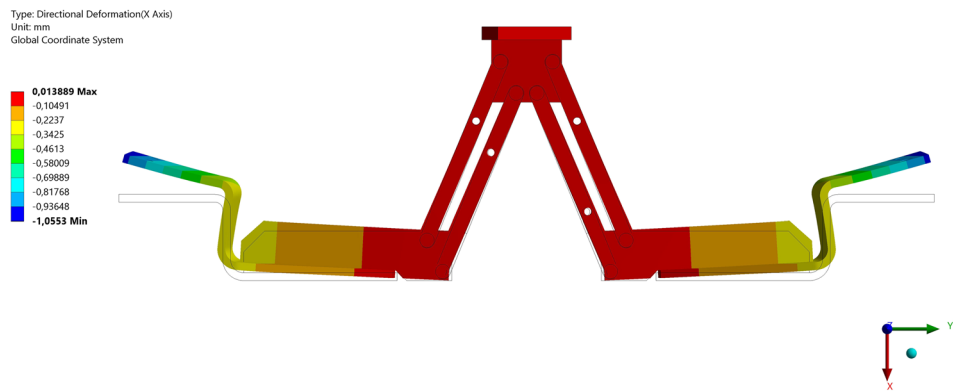
(a) *Horizontal displacements distribution in top view, to show the support structure's deflection due to the contact force (in augmented scale)*
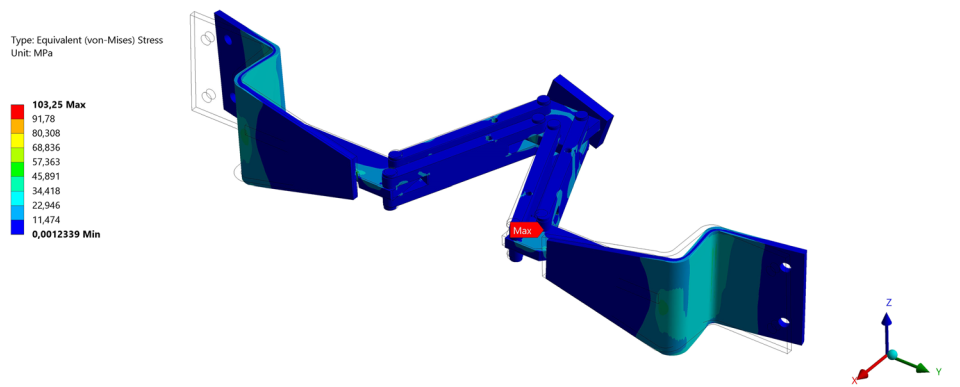
(b) *Equivalent Von Mises stress distribution*

CCs support plates determines a maximum horizontal displacement of 1.05 mm, which is under the limit of 3 mm needed to avoid the contact between the metal supporting structure and the CR. The contour plot of the equivalent Von Mises stress distribution in Fig. 19b shows that the maximum value on the curved surfaces of the CCs support plates is low (about 50 MPa) and the global maximum of 103.25 MPa, measured on one pivot pin for connection between central links and support plates, is under the limit imposed by its stainless-steel yield strength of 190 MPa, with a safety factor of

$$n = \frac{190 \; \frac{MPa}{103.25 \; MPa}} = 1.84 \qquad (4)$$

Therefore, CA can withstand the applied loads and FR 1.4 with its lower level ones are verified.

3.3 Prototyping and physical operation simulation

The successful structural verification of the system and sub-systems has allowed to proceed to the realization of a physical prototyping for physical operation tests. It has been mainly made of 3D-printed components, exploiting an Ultimaker printer and its related software. The typical stages of an additive manufacturing process have been followed:

1. Parts' 3D model import in Cura Ultimaker environment
2. Printing data preparation and set-up
3. Machine preparation and set-up
4. Printing
5. Post-processing for supports removal and threads manual realization

A mock-up made of aluminum bars has also been assembled in order to mount both the Charging Arm prototype and a purchased sample of the CR on it, such to carry out some operation simulations. The final prototype assembly is shown in Fig. 20.

The prototype has been tested following the same Test Cases of the dynamic simulation (see Sect. 3.4) and with a manual actuation of the mechanism (i.e. manual movement of LDBs), since motors have not yet been implemented in the mock-up. The physical tests have showed good performances and confirmed the results already achieved by dynamic simulations, being able to:

- Symmetrically be opened/closed (FR 1.1).
- Correctly move vertically, keeping its symmetry (FR 1.2).
- Correctly open/close and move vertically with just one LDB translation (FR 1.1.2).
- Correctly insert the CCBs in the CRCs in most tests, even self-compensating misalignment and interference (FR 1.3), tested by varying the height of the CA with respect to the CR.

Further tests will be carried out with motors and charging arm design components in the actual operative position (i.e., on TIM Bogie) in order to definitely assess the correct kinematic, dynamic, and electric operation of the product, also evaluating the actual feasibility of charging TIM during its motion.

3.4 Maintenance simulations in a virtual reality (VR) environment

The last step of the testing stream and of the whole product development process has been the simulation of maintenance operations in a Virtual Reality (VR) environment. The aim of this stage has been the validation of the FR 1.1.1.1, requiring a position of the driving motors on the bogie easy to be manually accessed in case of manual unlocking needs. In Fig. 21, the position of the screw drive motors is shown.
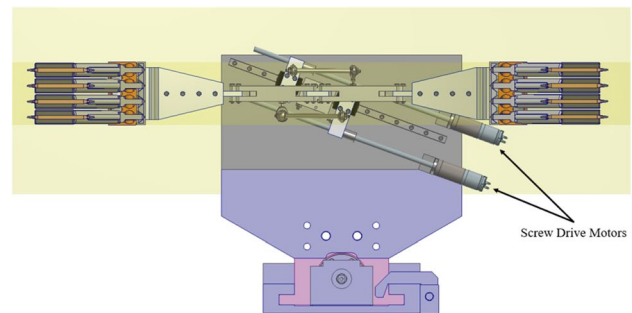

Fig. 20 Prototype made of 3D-printed components (top view)

Fig. 21 Position of the screw drive motors on the bogie to be validated

The VR software IC.IDO has been employed to perform the simulation, importing in it a digital environment including the following:

- A sector of the tunnel
- A sector of the monorail with charging rail
- The battery wagon's frame with charging arm mounted on it
- A 50th percentile German male mannequin

The ergonomics of the operation has been evaluated through the Rapid Upper Limb Assessment (RULA) method, which, developed by Corlett and McAtamney in 1993 [14], is a method of posture analysis that focuses on the upper body, but also includes the lower body [15]. It allows to assign both an operation's ergonomic overall score and specific scores for upper arms, lower arms, and wrists, together with posture of the neck, trunk, and legs, as well as another numerical rating for additional factors that strain the musculoskeletal system, such as repetitive action, static loading and force exertion [16]. Although this postural analysis process normally requires the intervention of an experienced ergonomist who observes workers' actions, a tool to automatically calculate these various risk indices on the basis of the information related to the kinematic of the worker's body (posture) is embedded in many software, including the employed one IC.IDO [17]. The graphic output and the RULA scores obtained by the simulation have showed that the motors can be manually accessed and maintained, easily and in an ergonomic way, through the help of a 425-mm high stepladder, as shown in Fig. 22.

Finally, a virtual immersive experience has allowed to virtually enter in the environment imported in the software,
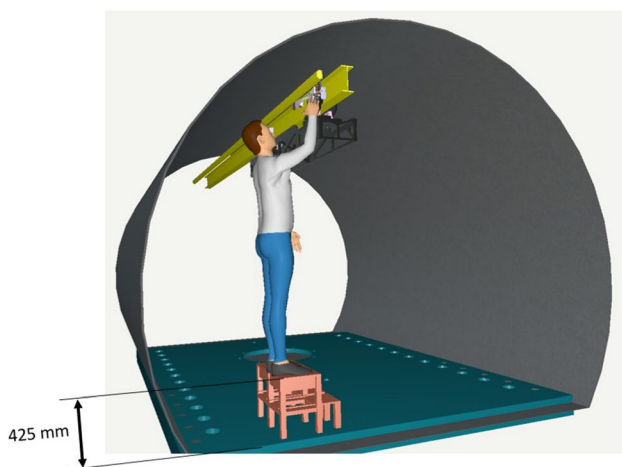
Fig. 22 The maintenance operation simulation in virtual reality (VR) environment shows that the operator can manually access the motors in an ergonomic way with the help of a 425-mm high stepladder

through the use of a head-mounted display (HMD) and controllers and with the possibility of having both the first and the third-person perspective of the maintenance operation conducted by the operator, as shown in Fig. 23.

4 Conclusion

A new charging arm configuration for Train Inspection Monorail travelling in LHC tunnel at CERN was needed to solve the issues of the previous version and overcome its limits. A rigorous model-based system engineering approach, with the V-model guiding the product development process, has allowed to realize a new concept appearing compliant with requirements and able to take a big step forward compared to previous version, as confirmed by simulations and physical tests carried out as part of the V-model's testing stream. The verification and validation process has been focused on the digital twin of the product, namely its virtual model, and this has allowed to realize a unique physical prototype, minimizing the expenses and time otherwise required in case of multiple tests with several ones. In fact, the positive results achieved, summarized in next section, envisages the possibility to validate the charging arm functioning and launch the product after just a limited number of on-site acceptance tests.

4.1 Results and discussion

After intense phases of requirements and constraints analysis and concept design, with many different concepts developed, the new charging arm solution implemented appears to provide dedicated features such to fulfill each functional requirement. The correct operation of these features and their capability to address the related requirements have been verified through a number of virtual and physical simulations. A traceability matrix (Fig. 24) has been employed to manage and keep track of requirements, ensuring the fulfillment of each one and showing how each simulation verifies each requirement.
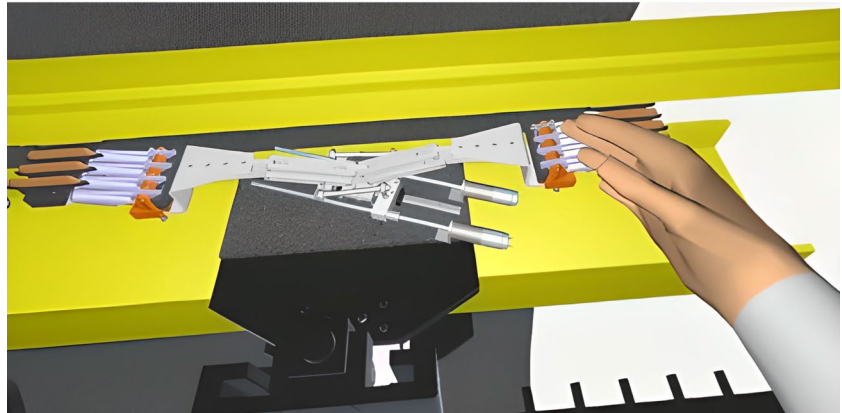
The matrix includes, for each FR, the feature addressing the requirement and the correlation with the simulation test case verifying the requirement. The simulations' test cases are the ones defined for the dynamic simulations in Sect. 3.4 and are re-called in the matrix legend. It can be seen that:

- virtual dynamic simulations validate the mechanism's kinematics and prove it guarantees correct opening/closing, vertically adjustment and compensation of issues of insertion of CCBs in CRCs as required, without excessive loads on the subsystems. They also verify commercial parts against applied loads.

Fig. 23 Immersive experience in the virtual environment
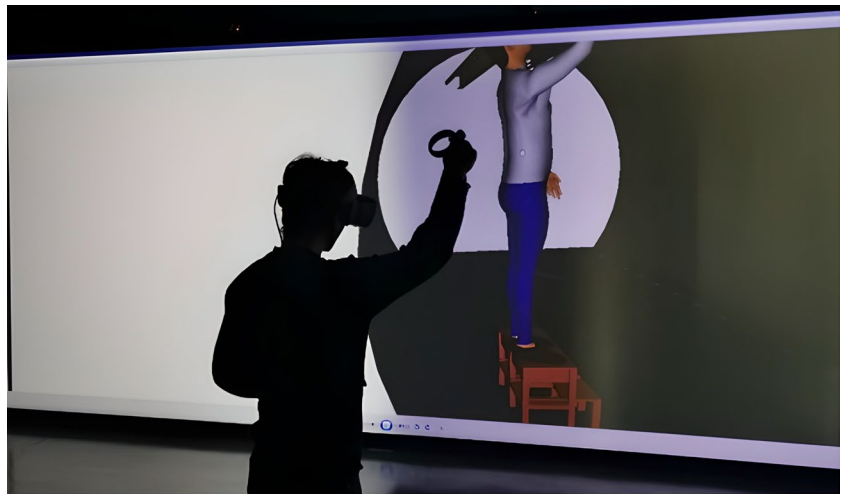
(a) *Use of Head Mounted Display (HMD) and controllers to experience the virtual environment, which is also showed on a Powerwall*

(b) *First-person perspective of the maintenance operation conducted by the human operator*

Fig. 24 Traceability matrix

- structural simulations with Finite Element Method (FEM) verify the system can withstand both resting loads (own weight) and operational loads (own weight and contact pressure against CR).
- physical test sessions carried out with the physical mock-up confirm the previous results.
- Virtual reality simulations and immersive experience positively verify motors' manual reachability and, hence, feasibility of manual unlocking intervention.
- The implementation of a commercial current collector designed to operate while sliding up to a velocity of 6 km/h envisages new charging arm can charge TIM in motion. However, this required function has not yet been verified since the Charging Rail purchased prototype is too small to perform reliable tests. Further virtual and physical tests will be done to validate this requirement, employing real operative location and conditions. The charging rail path should be long enough to guarantee that charging arm is able to keep charging active also in case of charging rail's curves and deformations, so as to completely verify the requirement.

The results already achieved are positive enough to conclude that this new charging arm configuration can overcome the limits of the previous one and fulfill each design requirement. However, an on-site test session in the real operative condition is required to complete the validation process, verifying the remaining requirements and confirming the verification of the others.

4.2 Limitations and future work

Despite the positive results of the testing stream, the proposed charging arm design is also characterized by some drawbacks. It is a complex mechanism, made of several small parts distributed in a very narrow space; hence, a well-performed session of on-site tests with multiple iterations is necessary to validate system's reliability. Moreover, the realized charging arm prototype has showed non-negligible deflections under its weight force during physical simulations, due to the cantilevered configuration of moving links and current collectors; however, this is caused by the use of 3D-printed plastic as structural materials, while minor, acceptable, deflections are foreseen by structural simulations on real charging arm made of metal parts.

Cabling route has been considered during the design but a more detailed analysis, study, and design of cables path and fixing positions are still required. Next activities will also include the study and development of motors' control mode with selection, purchasing, and implementation of absolute sensors for position monitoring instant by instant. Selection process will focus on both linear sensors to directly monitor

LDBs' position and rotary encoders to track driving motors' angular position.

The most important part of the future activities will be the construction of the first unit of new Charging Arm, with both the purchased and the in-house produced metal parts, and its acceptance test in the real operative location and working conditions. Only this step will allow to assess the capability of new charging arm to charge TIM during its motion. This still appears a difficult procedure which can only be achieved if the mechanism is able to constantly keep the correct contact between CCBs and CRCs against variations of charging rail shape, avoiding both detachments, with risk of sparks due to electric arcs' formation, and excessive contact pressure, which could compromise contact conditions and structural integrity of materials and components. A correct execution of this procedure can be aided by the addition of pressure sensors to the control system, in order to always keep the CCBs to CRCs contact pressure in the optimal range and correct it by acting on the motors if required. On-site acceptance tests will also allow to confirm the feasibility of the motors' manual unlocking procedure.

The activities have been carried out at CERN premises and laboratories in Geneve (Switzerland), except for the simulation and immersive experience in VR, performed at MarteLab of Federico II University of Naples (Italy).

Declarations

Consent to participate No participation is included in this research.

Consent for publication The authors agree with the Copyright Transfer Statement.

Conflict of interest The authors declare no competing interests.

Human and animal rights and informed consent The consent of this research is not involved with the human and animal participants.

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