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Assessment of navigation technologies for automated guided vehicle in nuclear fusion facilities

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HIGHLIGHTS

- Evaluation of well-known and mature navigation technologies used by Automated Guided Vehicles (AGV) in industry.
- Description of navigation technologies based on a physical or virtual path.
- Critical assessment of navigation technologies in the framework of fusion facilities.

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ABSTRACT

Nuclear fusion power plants require periodical maintenance, including the remote handling operations of transportation performed by automated guided vehicles (AGV). The navigation system becomes a key issue given the safety constrains of the heavy load to be transported in the complex scenarios, such as the reactor building. This work presents well-known and mature navigation technologies used by AGV in industry: with a physical path (e.g., wire/inductive guidance, optical line guidance and magnetic tape guidance) and with a virtual path (e.g., laser based, motion capture, inertial, magnetic-gyro) to be followed by the AGV during the operations of transportation. A critical assessment is also presented regarding the performance of these technologies against the operational requirements and safety demonstration in the framework of fusion facilities like ITER (International Thermonuclear Experimental Reactor) or DEMO (DEMOnstration Power Station).

1. Introduction

Maintenance in nuclear fusion plants is particularly challenging due to the fact that both the materials and the space surrounding the reactor are activated. Thus, all maintenance operations within the activation time window have to be performed by a Remote Maintenance System (RMS). This paper focuses in one component of this system: the transportation of activated materials between two different locations.

This transportation is performed by vehicles that, due to the dimensions, weight, and shielding requirements of the typical payloads, are significantly large and heavy. In addition, the typical low clearance between the building structure and these vehicles imposes high reliability requirements to them. Thus, an autonomous (or semi-autonomous) Guidance, Navigation, and Control (GNC) system is often considered to guide these vehicles during transportation tasks. We define the Navigation problem as the one of determining the position and orientation of the vehicle with respect to a reference frame, the Guidance problem as the one of obtaining the trajectory from this position and orientation in order to follow a given path, and the Control as the one of computing the actuation to be sent to the vehicle motors in order to follow this trajectory.

This paper focuses on the navigation component of the GNC system of these vehicles. This is a well-studied problem, having reached a very high technological maturity with wide-spread use in the manufacturing industry, mostly in the automobile one. These vehicles are known to these communities as AGV [1]. So, most of the technologies discussed in this paper were first introduced at an industrial level in these vehicles.

The goal of this paper is to perform an assessment of a selection of these mature technologies, with respect to their applicability to the RMS of nuclear fusion plants. In addition, we will propose a navigation solution supported by a trade-off analysis, in order to address the high reliability requirements demanded by these plants. Even though the technologies discussed in this paper are applicable to a broader range of nuclear plant facilities, we will use the ITER (International Thermonuclear Experimental Reactor) as a case study. We will also borrow some terminology specific

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to the ITER [2,3]. The same technologies are being addressed in the preliminaries studies of DEMO (DEMOnstration Power Station), which is intended to build upon the ITER experimental nuclear fusion reactor. The objectives of DEMO are usually understood to lie somewhere between those of ITER and a "first of a kind" commercial station, [4,5].

This paper is organized as follows. The Section 2 summarizes the main requirements for a transportation system in nuclear facilities. The Section 3 presents the technologies available off-the-shelf, being some of them broadly used in industry, benchmarked in Section 3.1. The proposed solutions are based in two approaches: physical paths or virtual paths, which are detailed in Section 3.1.1 (wire/inductive guidance, optical line guidance, and magnetic tape guidance), and Section 3.1.2 (laser based navigation, motion capture systems, inertial navigation, and magnetic-gyro grid navigation), respectively. Seven different navigation solutions are presented in Section 3.2 and detailed in its Subsections. The Section 4 presents the robustness and integrity issues with impact to the navigation solutions, in particular the radiation and other environmental conditions, such as residual magnetic fields, temperature, humidity and pressure. The Section 5 describes the trade-off criteria (Section 5.1), the results of evaluation based on that criteria (Section 5.2) and the proposed solution (Section 5.3). The Section 6 wraps up the paper with some conclusions.

2. Problem statement

The operations of transportation are performed by vehicles in two modes of operation: *nominal* and *non-nominal*. Nominal mode concerns the transportation between two locations along a previously defined path. These operations are expected to be the most frequent. Ideally, in the absence of any failure, all operations are of this kind. The non-nominal mode includes all other situations, namely when unexpected events occur, such as an excessive deviation from the predefined path. In these situations the vehicle may be required to follow a path different from the predefined ones in order to resume the nominal mode. Non-nominal mode also includes rescue operations, e.g., the motion of a rescue vehicle to perform remote maintenance on a transportation vehicle.

Taking into account the example of ITER, there are two main buildings: the Tokamak Building (TB), with the reactor, and the Hot Cell Building (HCB), which can be a single or a set of buildings for the storage, repairing and refurbishment of equipment ad components, as illustrated in Fig. 1. The TB has galleries with a circular shape and docking stations around the reactor. The buildings have different levels, which require a lift system to transport the vehicle between them. During the transportation, the load is inside of a cask, for shielding purposes, and carried on by the cask transfer system (CTS). A pallet provides the ability of the CTS moving beneath the cask and transport it, when necessary, as illustrated in Fig. 1. In ITER, the dimensions of each level of the TB is equivalent to a soccer field, while the CTS is similar to a bus, but with a total weight that can reach up to 100 tons.

The CTS shall provide means for remote navigation to support the transportation of loads along the galleries of the buildings, from/to docking stations, with the following requirements (extracted from the Technical Specification document for the Business Case of F4E-OMF-0577 Cask and Plug Remote Handling System of ITER):

- The CTS shall move over a step of ± 2 mm and be able to cross a gap (assuming lifts in the building).
- The CTS shall be designed for a minimum operational lifetime of 30 years, with replacement of consumable parts to cover use from machine assembly to decommissioning phase.
- Radiation sensitive items that are built into the CTS equipment (such as motors, sensors, cameras, lubricant, cables) shall have a minimum demonstrated radiation lifetime of 2000 h under the highest-level radiation conditions (this value is assumed as the reference through the paper).
- Where is can be demonstrated that a radiation lifetime of 2000 h for a given component is not achievable it shall be designed for ease of replacement.
- The CTS shall run in autonomous configuration by means of an on-board control system and power supply under monitoring of the supervisory control system.
- The CTS shall be capable of being powered up after a power outage without any need for re-calibration.
- The CTS shall provide means for its remote rescue where necessary. All CTS equipment shall be recoverable or rescueable in the event of failure.
- The CTS shall avoid collision with other equipment to prevent damage.
- Following system failure, or activation of an Emergency Stop, the system shall enter a safe-state, whereby the motion is stopped and the equipment is holding load.
- The CTS shall operate within a residual magnetic field of up to 1 mT.
- In order to simplify the maintenance of the CTS and minimize spares inventory, items such as radiation hard components (such as motors, sensors, lubricant and cables), and others (such as bolts, connectors etc.) shall be standardized as much as possible.

The next sections detail the navigation methodologies to accomplish the previous requirements.

3. Description of proposed solutions

Guidance, navigation and control are the three principal components that support the proper motion of the CTS. Other important aspects requiring consideration include, among others, communication, obstacle detection and monitoring. Guidance involves the generation of optimal paths and velocity profiles for the CTS allocated missions, taking into account the constraints of the available space for navigation. Previous works have been done, with the development of motion planning algorithms to compute optimized paths for large-scale vehicles in cluttered environments, [6–9].

Navigation methodologies provide the CTS localization (position and orientation), required by the control algorithm, to minimize the tracking error relative to the reference optimal path previously defined for each mission. This can be implemented using on-board or off-board systems [10]. This is the issue discussed in this paper. Even though the control algorithms will not be presented, discussion on the required computational load of the on-board or off-board controller will be taken into account in the trade-off analysis of the navigation methodologies, in Section 5.

This section describes all the navigation methodologies identified as being potentially suitable for use within reactor buildings. It then details integrated options that comprise a primary and secondary navigation system, based on the initial list of methodologies identified. The pros and cons of these integrated options are listed, as well as the key equipment within each.

3.1. Technology benchmark

The paths to be followed by the CTS are the input of the CTS controller, and aim to minimize the path tracking error. There are two distinct navigation concepts available; based on either physical paths or virtual paths. These are discussed in the following sections of this report. For each concept, different technologies are available.

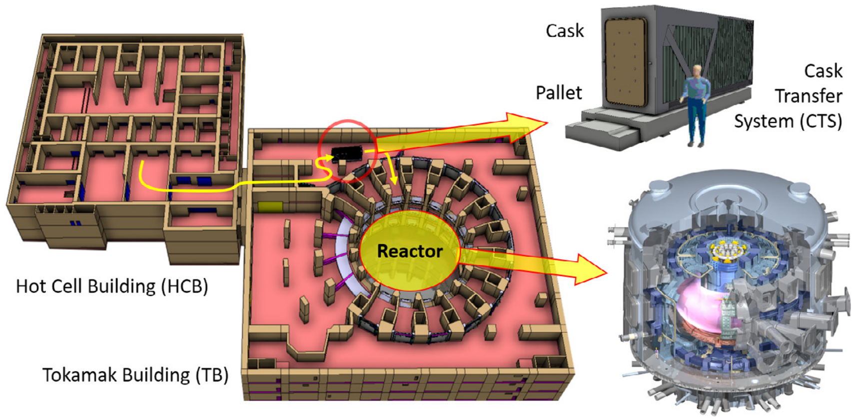

Fig. 1. The tokamak and hot cell buildings of the ITER, its reactor and the cask transfer system for maintenance operations of transportation.

Concept 1 is based on a physical path system. The methodologies under concept 1, known as line guidance, are characterized by having pre-determined static routes, to be followed by the CTS, set out on the floor of the facility. These are a priori determined by the GNC.

Line guided vehicle navigation offers a simple, robust and accurate methodology. Whilst the vehicle remains on the defined route, the risk of collisions with known obstacles in the environment is low. This is due to the fact that localization errors are substantially lowered; at any time, the vehicle "knows" it is on its track and therefore not in a forbidden location. Moreover, the steering sensors can be used to trigger an emergency stop as soon as they detect a deviation from the defined path. This can be done with a simple, low-complexity control system. Line guided methodologies use sensors located along the CTS longitudinal axis together with simple control algorithms running on board to keep the vehicle on its designed path.

Being statically defined at floor level, navigation based on this concept does not provide full flexibility to change the path, and to define new paths that might be required due to the experience gained in the operation of the reactor, or to adapt to changes in the HCB whose design is not yet finished. However, different methodologies based on physical paths present different levels of flexibility for changes.

The Concept 2 utilizes virtual paths, i.e., the optimal paths to be tracked by the CTS are only defined at computer level, and thus can be easily changed, even though the set of optimal paths for nominal operations might be evaluated and pre-defined before any operation starts. The routes can be adapted to either closely follow the routes defined in Concept 1, or utilize alternative paths if required.

To enable effective control over the movements of the CTS using Concept 2, the vehicle control system requires accurate data on the position and orientation of the CTS relative to the buildings (localization data). This information is generated through the internal or external sensors (lasers or cameras). The most common technologies for managing vehicle movement and tracking accuracy, such as sensors and control systems, are more complex in virtual navigation systems (Concept 2) relative to those in physical systems (Concept 1). Because virtual paths can be generated whenever necessary, Concept 2 is capable of supporting the required motions of a rescue vehicle, even those outside of the normal range of movements anticipated. This will allow vehicles to access any area necessary to resolve unexpected situations. The reliability of this system can be readily tested in the Virtual Reality (VR) system of the Remote Handling (RH) control room before being implemented in the CTS.

3.1.1. *Technologies based on a physical path*

The common line guidance technologies, described in the following sections and illustrated in Fig. 2, are:

1. Wire/inductive guidance,
2. Optical line guidance, and
3. Magnetic tape guidance.

3.1.1.1. Wire/inductive guidance. Wire/inductive guided vehicles follow a wire embedded in the floor with a specific frequency of current running through it (Fig. 3). This creates a magnetic field around the conductor itself that can be detected by a sensor (second image of Fig. 3), [11]. Guide wires are laid out in a slot cut in the ground in a loop and connected to a frequency generator installed in each level of a building.

Steering antennas on the CTS are used to detect the magnetic field generated by the current. The deviation of the antenna(e) from the wire (proportional to the differential mode of the electric voltage induced on the two coils of each antenna) is used to control the CTS bearing. The movement of the CTS at cross roads, or where a particular maneuver is required, is achieved through the detection and interpretation of unique codes situated at particular locations. The codes are emitted by passive transponders installed in holes drilled on the floor and sealed. The signals are picked up by antennae placed on the CTS. Motion commands to the CTS for a given mission are dispatched through the wireless communication system.

This methodology has a number of benefits including:

- It is highly robust;
- It can achieve very good accuracy on path tracking (±3 mm);
- It has built-in emergency stop features; and
- It is a mature technology (>60 years; as for other values, the date of this paper is used as reference) with well-established suppliers (AGV suppliers).

The wire guidance is a well known and mature technology used in industry, as the examples depicted in Figs. 4 and 5.

However, it is recognized that this technique is highly limited in its ability to accommodate route changes. This would require access to the facility and re-routing of wires embedded in the facility floor.

3.1.1.2. Optical line guidance. When using optical line guidance, the desired path is physically delineated at floor level by a painted or taped line that is recognized by modern cameras (second image of Fig. 2).

Cameras on the CTS are placed along its longitudinal axis that is associated with the drive and steering blocks. The cameras

Fig. 2. Line guidance principles (from left to right): wire and optical guidance (http://www.goetting-agv.com/) and magnetic tape guidance (http://www.transbotics.com/).

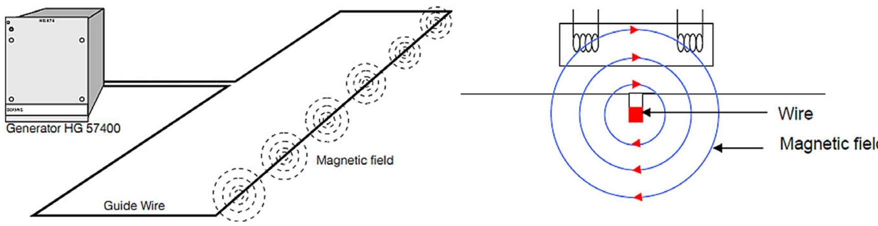

Fig. 3. Frequency generator and wire installed on a cut on the ground (left figure taken from http://www.goetting-agv.com/ and right figure from [12]).

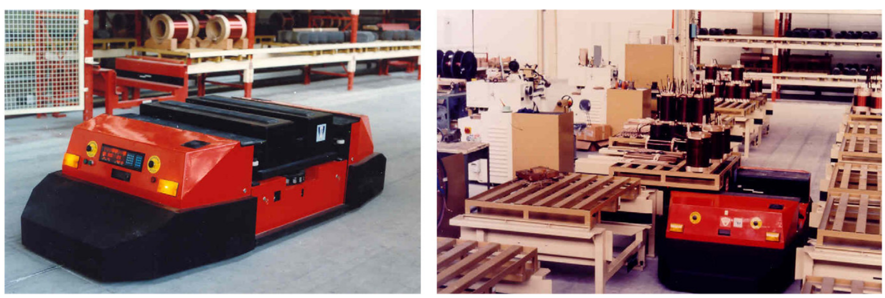

Fig. 4. An automated guided vehicle application in industry, the first of its kind in Portugal [1990–1991], with a fleet of four vehicles and wire guidance navigation providing material transportation between 120 operational locations and the two automatic warehouses of Efacec's electrical transformer plant.

Fig. 5. Photos of an AGV designed and build by A-VT Europe NV using line guidance (http://www.a-vt.be/).

together with an image-processing algorithm (which runs on-board), detect the deviation of the CTS relative to the track. Branching from the original track can be detected as well as the recognition of coded tracks. For absolute position information along this guidance line an additional system such as a small transponder system, is required. This network of transponders plays the same role of those used by inductive guidance and, for the same paths, can be installed at the same positions.

This methodology has a number of benefits including:

- Good accuracy on path tracking;
- It is based on a passive physical path that does not require a power supply;
- It utilizes a mature technology (>50 years) with well-established suppliers, (AGV suppliers); and
- It is relatively flexible to cope with path changes, as it does not require re-routing wires and channels in which the wires run.

However, in industry, the use of AGVs with optical guidance is not as common as inductive/wire guidance. The continuous operation of the CTS on top of the painted or taped lines may result in their degradation. As a result, it may be necessary to apply a protective cover, or periodically repair/ replace the lines.

3.1.1.3. Magnetic tape guidance. An adhesive magnetic tape is laid on the surface of the floor (third image of Fig. 2). The tape creates an invisible magnetic field, detected by sensors on-board. This methodology is immune to dirt and unaffected by lighting conditions. It provides not only the path for the vehicle to follow but, can also include markers installed on the floor to tell the vehicle to change lane and also speed up, slow down or stop. This is a passive system since it does not require the medium to be energized as wire does. The tape is easy to lay and modify.

Track changing at crossroads is however more difficult than in the wire, inductive or optical guidance methodologies. The consecutive operation of the CTS on top of the magnetic tape degrades it, and thus the tape will require periodic replacement.

3.1.2. Technologies based on a virtual path

The common virtual path technologies, described in the following sections, are:

1. Laser based navigation,
2. Motion capture systems,
3. Inertial navigation and
4. Magnetic-gyro grid navigation.

3.1.2.1. Laser based navigation. This is a remote sensing technology that measures the distance and reflectance of a target by illuminating it with a laser and analyzing the reflected light. Localization based on lasers is commonly implemented in industry with on-board lasers installed on the vehicle and passive reflective markers fixed on the walls. The localization is computed using triangulation (first image of Fig. 6). The same approach with laser technologies can be used with off-board lasers installed within the local environment. These detect passive markers installed on precise locations of the CTS (second image of Fig. 6). With on-board lasers, CTS localization is estimated in the on-board computer unit. These same sensors can also be used for obstacle detection. With lasers installed within the local environment for CTS localization, the data acquisition is done off-board, [13]. The acquired data is sent through a wired system to the control room, where the data of different laser sensors is integrated to compute the localization of the CTS. The off-board controller on the control room sends the motion commands to the CTS by the wireless communication system.

With laser technologies, either on-board or off board, absolute localization of the CTS is provided with an update rate of 0.1 s and accuracy of around 2 cm. When localization data is combined with data from odometers in the CTS wheels, accuracy is improved. Lasers have good range (≈80 m) commensurate with reactor building dimensions. Laser based navigation supports path following in any virtual path, pre-determined or otherwise. As a result, this approach is capable of fully supporting any type of motion required for rescue operations.

Off-board lasers are ready to support operations with the already considered different CTS typologies, and any other type of vehicles, e.g., the rescue vehicles. Off-board lasers can be easily tested and calibrated remotely, without human intervention in the scenario.

The laser guidance is quite new when compared with the wire guidance, but still well known and used in industry, as exemplified in Fig. 7.

3.1.2.2. Motion capture systems. Motion capture systems (see Fig. 8), comprising a camera network and a central processing unit, are becoming a de facto standard for the collection of ground truth of moving targets. Typical applications include capturing human motion data and control of fleets of unmanned aerial vehicles (UAV). These systems are typically capable of delivering millimeter precise localization at frame rates of hundreds per second.

This method allows a precise localization of the target object, as long as enough landmarks are visible by a sufficient amount of cameras, [15]. In terms of equipment, this system requires the installation of cameras and landmarks; both of which are easily obtainable as commercial off-the-shelf (COTS). Computer vision algorithms are computationally heavy to process, growing linearly with the amount of cameras. However, motion capture systems are currently available as COTS with very high performance levels.

The setup of a motion capture system would comprise a network of video cameras installed inside the reactor building, together with landmarks placed on the CTS. The cameras determine the relative position of these markers from which, given their absolute position with respect to the environment map, it is possible to estimate the CTS absolute position. This estimate may be further combined with odometric (and/or inertial) measurements, transmitted wirelessly from the CTS.

Based on range of benefits originally identified for this technique, it was initially proposed that it should be taken forward as a potential candidate for the secondary navigation system, and therefore subject to a more detailed trade-off analysis. Due to the requirement for the cameras of the motion capture system to be fixed, it was recognized that it was not possible to install them within the CTS. For this reason, the motion capture system is withdrawn as a possibility for primary navigation.

3.1.2.3. Inertial navigation. Inertial navigation uses gyroscopes and accelerometers to measure rate of rotation and acceleration, respectively. Measurements are integrated once (or twice, for accelerometers) to yield information on the vehicle's position. Inertial navigation systems have the advantage that they are self-contained; that is, they do not need external references. However, inertial sensor data drifts with time because of the need to integrate rate data to yield position. As a result, any small constant error increases without bound after integration and the error increases with time, regardless of the vehicle speed. Inertial sensors are thus mostly unsuitable for accurate positioning over an extended period of time without periodic sensor calibration.

These methodologies are currently used in external environments for motions in 3D, and are not so common in the AGV industry. For these reasons, this technology will not be considered in the trade-off analysis.

3.1.2.4. Magnetic-gyro grid navigation. There is a set of navigation methodologies whose basic principles are between the line guidance and the free roaming approaches. In one hand they are not supported by any physical path defined at floor level but, on the other, rely on dead-reckoning and inertial measurement sensors for absolute localization estimation (dead-reckoning is the process of determining an object's current position by projecting trajectories and speeds from known past positions, and predicting future positions by projecting the current trajectory and speed). Both dead-reckoning and inertial measurement techniques require periodic calibration during a normal journey as they have cumulative errors. This calibration may be provided by sensors/devices installed at floor level, usually in a grid pattern.

The magnetic-gyro grid navigation could be used by the CTS through the installation of magnet position sensors on the CTS. These would detect the magnetic field generated by small magnets installed in the facility floor in a grid pattern. Additionally odometers in the driving and steering wheels, and a gyroscope to keep the CTS heading direction continuously under control will be required.

Encoders on the drive and steering wheels, which provide information on traveled distance and orientation change, support position and orientation calculations. They are commonly used to provide continuous localization of vehicles such as the CTS. The main drawback of this option is that position and heading errors are cumulative, i.e., the extent of the error increases along the trajectory. Such errors can include wheel slippage and changes in wheel diameter due to load variations. As a result, it is necessary to undertake periodic calibrations to correct possible inaccuracies. Calibration is undertaken through the use of external reference points based on a grid of magnets embedded on the floor in a grid pattern, with a dully-defined spacing and well-studied positioning.

For further orientation accuracy, a rate-gyro unit can be installed on the CTS, providing CTS heading relative to a calibration location. Rate-gyros are known to have bias drift that increase with time; even when the vehicle is not moving. Typical drift values may range from 1°/s to 0.01°/h, with the cost increasing when the drift bias decreases. The rate-gyros require periodic calibration due to this drift. This calibration may be provided by the magnets (if their magnetic fields are equally aligned) or in known locations, e.g., ports, and in battery charging location.

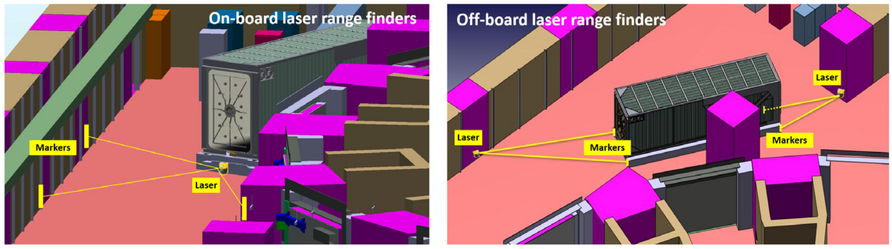

Fig. 6. Lasers sensors installed on the vehicle and markers on the walls (left image) and lasers sensors installed on the walls and markers on the vehicle (right image).

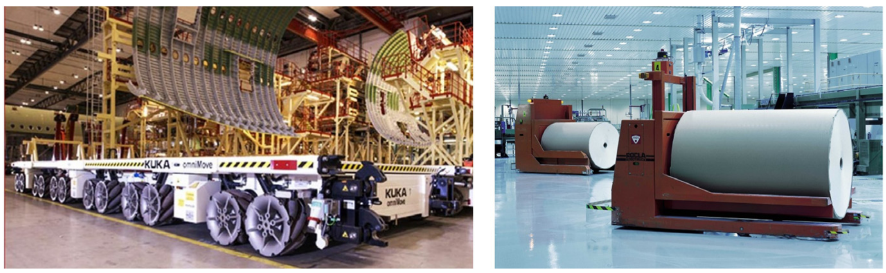

Fig. 7. Examples of laser guided vehicles (from left to right): KUKA industrial robots (http://www.kuka-omnimove.com/), image obtained from [14], and Efacec AGV to transport paper reels at Soporcel (http://www.efacec.pt/).

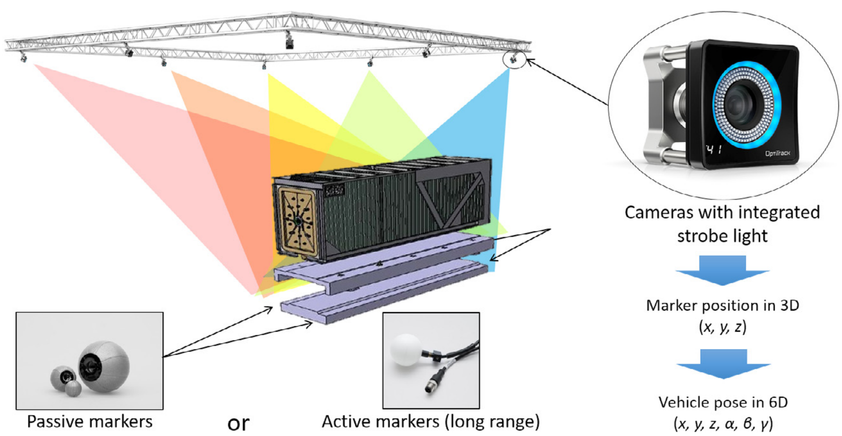

Fig. 8. Working principle of the motion capture system.

Table 1
Navigation solutions with primary navigation based on a physical path concept and secondary based on a virtual path concept.

	Solution 1	Solution 2	Solution 1 + 2
Primary = **physical path**	wire/inductive guidance	optical guidance	wire/inductive and optical guidance
Secondary = **virtual path**		lasers off-board	

Table 2
Navigation solutions with both primary and secondary navigation based on a virtual path concept.

	Solution 3	Solution 4	Solution 5	Solution 6
Primary = **virtual path**	lasers off-board	lasers on-board	magnetic-gyro grid	lasers on-board
Secondary = **virtual path**	motion capture system		lasers off-board	

3.2. Presentation of selected solutions

There are four possible combinations for primary and secondary navigation methodologies for the CTS, based on the combinations of the two concepts (physical and virtual path). Physical path based navigation does not support the entire flexibility required to support motion of a rescue vehicle or any other vehicle that has to move outside the nominal paths, and thus all possible solutions with Concept 1 for secondary navigation, e.g., wire/inductive and optical guidance, are withdrawn. Based on the presented technologies, the following seven solutions presented in Tables 1 and 2 are trade-off.

Solution 1, Solution 2, and Solution 1 + 2 share the same secondary navigation methodology, and have a primary navigation based on a physical path. Therefore the comparison of the three solutions only differs on the primary, as depicted in Table 1. This also happens for the pairs of Solutions 3 and 4, and Solutions 5 and 6, as depicted in Table 2.

It should be noted that the solutions that use off-board lasers or a motion capture (MOCAP) system either as primary or secondary navigation methodologies, can also support the navigation of a range of vehicles if required. This extends to rescue vehicles, and other vehicles not considered in this paper.

3.2.1. *Solution 1, solution 2 and solution* 1 + 2

Primary for solution 1	=	Wire/inductive guidance
Primary for solution 2	=	Optical line guidance
Primary for solution 1 + 2	=	Wire/inductive and optical guidance
Secondary for 1, 2, 1 + 2	=	Lasers off-board

3.2.1.1. Primary solution 1—wire guidance. CTS follows a wire that is embedded in the floor with a specific frequency of current running through it that creates a magnetic field around the conductor itself. The guide wires are laid out in a slot cut into the facility floor in a loop and connected to a frequency generator installed in each level of the TB (Fig. 3). The slot is cut to a depth of approximately 2.5 cm. The width of the slot is determined by the number of wires required; the typical width for a 4wire slot is 0.6 cm. The wire is positioned in the bottom of the slot, and a protective foam strip is squeezed down over the wire, preventing damage from CTS passing over. A frequency generator will be placed in each building level, and will be controlled via a control room.

Steering antennae on the CTS, placed along its longitudinal axis associated with the driving and steering blocks, are used to detect the magnetic field generated by the current. The deviation of the antennae from the wire (proportional to the differential mode of the electric voltage induced on the two coils) is used to control the CTS heading. Computation is done on-board and requires low CPU. Each CTS drive and steering wheels have two associated steering antennae that rotate with that steering block. The antennae are easily accessible on the CTS for replacement purposes. Its distance to the floor will have to be evaluated to properly shape the common mode of the voltage in the two coils and tune the accuracy in tracking the path. The antennae are close to the floor. The two closely located coils within them detect the difference of the magnetic field, at a specific frequency, generated by the current on the wire. Therefore, this navigation methodology is compatible with the (static) residual magnetic field of 1 mT during the maintenance phase.

Wires in each level will be powered-on during maintenance operations and when CTS motion is required only. During reactor operation, each wire section should be physically disconnected from its frequency generator to avoid having a closed circuit in a strong magnetic field. Switching in different sections of some of the longer wires can mitigate inductance issues on the buried wire, should they arise.

Guide wires positioned close to solid metal construction over long distances can distort the magnetic field, and therefore suppliers recommend that the distance of the steering antennae to the wire be equal to the metal free area below the wire.

Identification of detection points for turn at crossroads and maneuvers are achieved through passive transponders installed in holes drilled on the floor and sealed. Theirs unique code are identified by antennas, such as Radio-Frequency IDentification (RFID) readers, placed on the CTS. The transponders are supplied with energy each time a reader on the CTS crosses over. This generates the return signal of the transponder code to the reader. When detected with the CTS on top of the wire, absolute localization at that point is achieved. To minimize the number of transponders, and given that CTS can move forward and backward, two readers are installed on the CTS. A number around 20 transponders is required at each building level. Transponders do not support 2000 h of operation given the radiation exposure but they are easily replaceable. A painted dot on top of the hole where they are installed provides easy location identification for replacement.

A low-bandwidth track traveling data transmission could be used to create a radio data link between each CTS and the RH control room. The induction loop will be installed in the same cut as the guidance wire, and the CTS will be equipped with a transmitter/receiver as well as an antenna placed close to the communication wire along the CTS longitudinal axis. Given the low bandwidth, the fact that in sharp curves where the reading antenna deviates from the communication wire communication might not be possible, this data transmission will not be considered.

As there is no information on the material of the lift's floor, an assumption is made that no wire/inductive guidance will be used inside the lift. The proposed solution to navigate inside the lift and to overcome the gap in its entrance uses both steering antennae while the magnetic field generated by the wire in building is detected. When the front steering antenna loses the wire, and until the rear steering antenna detects the magnetic field, navigation will be done by sensors on the CTS. This could include ultrasound sensors or lasers installed on the CTS in its frontal and lateral panels that would measure the distance and orientation to the lift fixed structures. As soon as both steering antennae do not detect the wire, it can be assumed that both the drive and blocks are inside the lift and the vehicle is aligned.

Navigation proceeds using the on-board sensors, making primary navigation of Solution 1 self-sufficient for all nominal operations. An alternative for entering in the lift (see Solution 1 + 2) is to use optical guidance to enter the lift, as this methodology has no constraints to overcome the lift gap as a painted line can be easily painted or taped on the lift's floor.

The implementation of this primary navigation methodology is supported in the following principles:

- A unique nominal path along the gallery in each level of the building using one single frequency;
- Branching from the gallery to each port supported by a single frequency different from the previous;
- In a small number of ports, different branching paths are to be followed by each steering antenna;
- Transponders placed along and close to the wire for the identification of points with crossroads or maneuvers;
- Lift entrance is supported by sensors on-board, diverse from the steering antennae, or by using a different navigation methodology;
- A sequence of motion commands specifies the frequency to be followed by each steering antenna.

Motion commands to the CTS for a given mission, or part of a mission, are dispatched to each CTS through the wireless communication system. The set of motion commands for a given mission can be dispatched from the RH control room to each CTS prior to the mission start. However, the mission execution is monitored online at the RH control room as all parameters that impact safety functions will be monitored.

For this navigation methodology, the mission commands state:

- The frequency be followed by each steering antenna and the speed (or the speed profile) to be achieved until a given transponders is detected;
- Special actions to be taken when a transponder is detected. Example: start the navigation procedure of entering in the lift.

In case more than one CTS is moving in the same level of building (even though CTS is normally alone in each level), a traffic management system should be active. The distribution of transponders on the floors will be studied in such a way that only one CTS is allowed to travel in the section of a path between two given transponders.

For level B1 of TB three different frequencies are required, one for the gallery, one for the front and rear steering blocks for port entrance (in case both blocks can follow the same physical path) and a third one for the rear drive and steering block for port entrance in some ports.

The Fig. 9 illustrates a preliminary study for wire installation in level B1 of TB. From left to right—wire along the gallery; wire to be followed by both steering antennas; wire to be followed by the rear antenna; all the wires superimposed. The Fig. 10 describes how to switch from the wire of the common path along the gallery to the wire of a specific port, when the beacon is detected.

When each of the CTS front antennae (or rear antennae if the CTS is moving backwards) does not detect the magnetic field, or the common mode of its detected value is below a certain threshold, the low-level on-board controller will issue an emergency stop. This means that besides other actions, by switching the power of the frequency generator, which can be done at the RH control room, there will be no magnetic field associated to the wire, and an emergency stop is issued even in case the wireless communication system is not working. This is the built-in emergency stop referred in the text.

Other events, to be implemented at the CTS control system or the RH control room, will issue an emergency stop:

- No magnetic field detected (built-in emergency stop);
- An off-site power will switch off the frequency generators and thus issue an emergency stop;
- Detection of deviation from the path larger than a given threshold;
- Detection of over-speed;
- Detection of obstacles in the CTS predicted path;
- Lose of one sensor information (e.g., steering antenna, transponder not detected in its estimated location); and
- Detection of inconsistency on navigation data from the primary and the secondary navigation methodologies.

In case an emergency stop is activated, and braking function is actuated, the braking distance depends on the CTS speed and its total weight. After complete stop, CTS enters in a recovery state mode. To regain the physical path, each drive and steering block will rotate in such a way that all the steering antennas search for the magnetic field generated by the current on the wire. In case the physical path is detected, the on-board control system drives the CTS again to regain the path in semi-automatic mode. If, after the emergency stop, the guidance wire cannot be detected, the secondary navigation methodology (off-board lasers) will estimate the CTS location (position and orientation), while the CTS is driven in manual mode during a recovery state to reach the physical path.

The steering antennae can be shielded on top and lateral sides by lead with a thickness of approximately 1 cm to divide the dose rate by a factor of 2 or with a thickness of approximately 3 cm to divide it by a factor of 10. Other material than lead can be used, but keeping the same ratio thickness/density.

Pros:

- Proven and mature technology (>60 years);
- Wire is robust to radiation;
- Very good line tracking accuracy (down to ±3 mm);
- Built-in emergency stop (switch-off the frequency generator will issue, at CTS level, a CTS stop as the magnetic field is no longer detected by the steering antennas);
- Low CPU on-board required;
- Sustainability (availability on the market during the reactor lifetime);
- Integrity of the wire can be remotely checked, before each mission;
- Absolute localization in discrete location provided by the transponders;
- Relative localization to the path;
- No damages by the frequent top motion of the CTS wheels, especially in the crossroad entering the ports.

Cons:

- Guide wires positioned close to solid metal construction over long distances can distort the magnetic field. The problem can be mitigated by properly defining the distance of the antenna to the floor;
- There might be impact of the Tokamak magnetic field on the long wire of this navigation methodology, due to inductance/electrical issues during Tokamak operation. Mitigation can be obtained by switching a long wire in shorter sections. In all situations the wires shall be disconnected from the frequency generator during the Tokamak operation;
- No flexible for changes as the physical path is defined at floor level with a cut on the ground. Changes will require the opening of a new cut. If the entire wire is divided in smaller sections, the absence of flexibility is reduced as only smaller news cuts will have to be opened;
- Strong intervention in the scenario because requires floor cutting for the installation of the wires and installation of transponders in holes on the floor. No problems on positioning the wire during the commissioning, as there are companies specialized in floor cutting techniques that can produce clean, wire ready floor slots. Special machines with little noise, concrete dust, or water spillage have been developed;
- Integrity of the transponders cannot be remotely checked;
- Transponders do not support 2000 h of operation given the radiation exposure, but they are easily replaceable. A painted dot on top of hole where they are installed provides easy location identification for replacement;
- No absolute localization, (x, y, θ), in the TB referential except at discrete positions where position can be obtained from the reading of a transponder. However, it is known that the CTS is on top of the wire between two consecutive transponders and odometry provides the absolute localization with cumulative errors;
- Maintainability: replacement of the wire is difficult during the reactor lifetime. However, the transponders are easily replaceable;
- No support to the motion of other vehicles if they do not have steering antennas.

The required sensors/equipment, to be installed in the CTS or in the environment are: 2 × 2 Steering Antennas per CTS (2 per drive and steering block), RFID readers (2 per CTS), 2 Lasers or ultrasound sensors for the entrance/leaving the lift (on the CTS), wheel encoders on the CTS, Transponders on the floor (approximately 1 at each 1 meter of distance), Wire on the floor and Frequency Generator (1 per building level) serving all CTS in that level.

3.2.1.2. Primary solution 2—optical line guidance. The desired path is physically represented at floor level by a painted or taped line, with a good optical contrast, that is recognized by cameras that guide the CTS along the line. Cameras on the CTS, placed along its longitudinal axis, and an image-processing algorithm running on-board, detect the deviation of the CTS relative to the track. Branching from the original track can be detected as well as the recognition of coded tracks. For absolute position information along this guidance line an additional system, e.g. a transponder network, is required.

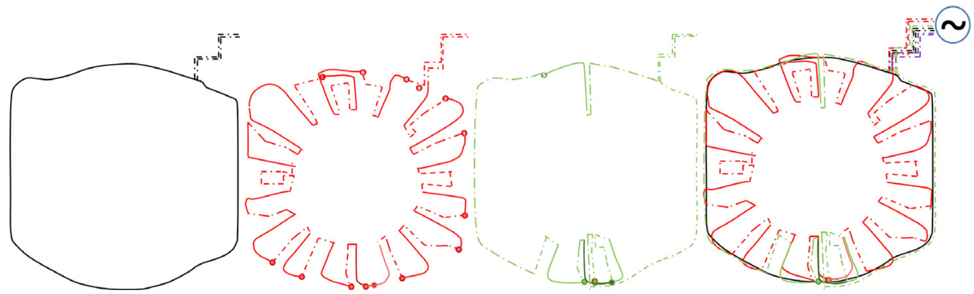

Fig. 9. Wire along the gallery of the level B1 in the Tokamak building of ITER (first image), wire to both wheels or only for the front wheel in some ports (second image), wire for the rear wheel in some ports (third image) and entire layout of wires (last image).

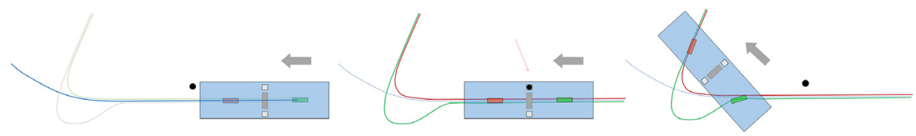

Fig. 10. Wire guidance switching: both wheels follow the same line along the main path (first image), a beacon is detected and, if programmed to, the powered wire is switched (second image) and the wheels follow different paths (third image).

The common track mark width is 20 mm. The distance of the camera lens to the painted line or track is around 100 mm. Two cameras per drive and steering block are required, as the CTS can move forward and backward. The camera should not be placed orthogonal (at right angles) to the floor, but should have a deviation from vertical of about 15° to 20° relative to the direction of travel. The usual opening angle of the cameras is 60° rectangular to direction of travel, corresponding to 120 mm at 100 mm mounting height. With the proposed CTS design, the cameras are easily accessible from both the front and rear panels of the CTS.

The processing of the camera images is done on-board, and the CTS on-board controller yields motion commands to the various wheels of the CTS. The motion commands of a mission are dispatched to the CTS through the wireless communication system, and similarly, the CTS localization relative to the painted line is transmitted back to the RH control room, for monitoring purposes, through the wireless communication system.

Passive transponders installed in holes on the floor and two RFID antennas on the CTS, play the same role as for the wire/inductive guidance navigation and will be installed exactly at the same locations.

The gap entering the lift is easily overcome by the optical guidance system that is also used to navigate inside the lift in whose floor a painted line will be designed.

The implementation of this primary navigation methodology is supported in the following principles, the same as for the wire guidance methodology:

- a unique nominal path along the gallery in each level of the TB using a single continuous painted line;
- branching from the gallery to each port and to the lift entrance supported by a painted line that branches from the one in the gallery;
- in some (few) ports different branching lines to be followed by each camera;
- transponders placed along and close to the painted line for the identification of points with cross-roads or maneuvers;
- Set of motion commands are dispatched to the CTS through the wireless communication system.

A centered painted line in the images of both cameras corresponds to a CTS in a non-forbidden area. The existence of a large deviation from the painted line in the image acquired by the cameras may yield an emergency stop at CTS level, with no intervention through the wireless communication system. After an emergency stop, and depending on the braking distance, the CTS can regain the painted line with a procedure similar to the one used for wire/inductive guidance. If this procedure fails, the CTS will change to the recovery mode. If the secondary navigation can secure the CTS localization, the CTS returns to the nominal mode and resumes operation, otherwise the CTS changes to the rescue mode. In the optical guidance methodology as the path is passive, there is no built-in emergency stop; i.e. it is not possible to deactivate the painted lines in any way.

Similarly to the wire guidance, the following events will initiate an emergency stop if the optical navigation system is in use:

- Detection of deviation from the path larger than a given threshold;
- An off-site power is detected by a timeout in the wireless communication system (until that the CTS still moves);
- Detection of over-speed;
- Detection of obstacles in the CTS predicted path;
- Lose of one sensor information (e.g., cameras, transponder not detected in its estimated location); and
- Detection on inconsistency of navigation data from the primary and the secondary navigation methodologies.

The pros and cons of this solution can be summarized as follows:

Pros

- Good accuracy on path tracking;
- Passive physical path, with no radiation related issues;
- Easy to install and to update/change, even though it would require local human intervention;
- Sustainability (availability on the market during the reactor lifetime);
- No issues entering the lift (interruption on the track can be overcome);
- The physical path is visible through the viewing system. Therefore it is visible at the RH control room;
- Localization relative to the painted track;
- Not influenced by metal on the ground;
- Not influenced by external light, as cameras are installed on the lower part of the CTS and are therefore shaded. To overcome this, integrated light-emitting diodes (LED) is used; and
- Mature technology (>50 years).

Cons:

- No flexibility to changes in the nominal paths. However, changes are easy to implement, particularly when compared with wire guidance;
- Absolute localization is limited to discrete points (if transponders are located along the track or track codes are used);
- Not sufficient to support motion of rescue vehicles or other vehicles outside the nominal paths, or those that are not equipped with sensors to follow the line;
- No built-in emergency stop, as the line is passive;
- Possible damages of the painted or taped line due to vehicles crossing lines (special in the crossing of the gallery, in the entrance of each port especially with a CTs with a large number of wheels); mitigation is achieved by protecting/covering the painted or taped line;
- The integrity of the network cannot be verified before starting a journey, but can be continuously checked along consecutive motion on top;
- Additional sensors (e.g. transponders) are necessary for longitudinal information;
- Transponders do not support 2000 h of operation given the radiation exposure, but they are easily replaceable; and
- Dirt may affect the system performance.

The required sensors/equipment, to be installed in the CTS or in the environment (TB) are: 4 Cameras in the CTS (2 per drive and steering block), Transponder antennas (2 per CTS), Wheel encoders on the CTS, Painted or taped line in the floor, Transponders on the floor.

3.2.1.3. Primary solution $1+2$*—wire/inductive and optical line guidance.* Wire and optical guidance are both physical navigation methodologies that are particularly advantageous in their ability to fulfill a range of safety requirements. During motion, the CTS is continuously evaluating on-board the deviation from the path. If the CTS deviates by more than a defined threshold from the mapped out path, an emergency stop is issued to ensure it remains inside the area allowed for navigation, and avoids collisions with the known obstacles within the facility. Inductive wire guidance is more common in industrial environments that use AGVs than optical guidance. However, optical guidance offers greater flexibility to change the path defined at floor level relative to a wire guidance system.

A brief comparison of the wire and the optical primary navigation methodologies using the main pros and cons above presented is summarized in Table 3.

The combined benefits of the implementation of Solution $1+2$, that equips the CTS with steering antennae (used with inductive wire) and cameras (used with optical steering) that links to the drive and steering blocks, are:

- Retains the level of safety and control offered by a physical path;
- Retains some flexibility to change nominal paths if required. This could either be during installation and testing in the non-nuclear phase, or following possible modifications required during reactor lifecycle.

Due to the relatively low cost of the sensors, induction wire and paint/tape line, it is not prohibitively expensive to equip the CTS with both the steering antennae and cameras which can then be linked to the CTS control system. The operator situated in the RH control room will have the ability to switch between these two navigation methodologies. This switch can also be achieved through the detection of a given transponder with which the CTS will come into contact.

Cross-roads (that occur at the entrance of the ports) and maneuvers (possibly close to some ports and at the lift entrance) do not represent any problem for the physical path based navigation, as CTS can move forward and backward and each wheel can follow a different path as illustrated in Fig. 10, assuming the kinematic model depicted in Fig. 11. The CTS has two drivable and steerable wheels, identified as "F"ront and "R"ear wheels, with the respective velocities (v_F and v_R) and orientations (θ_F and θ_R). The model in [8] entails that the wheels of the vehicle roll without slipping resulting in the constrain of (1).

$$v_F \cdot \cos\theta_F = v_R \cdot \cos\theta_R. \tag{1}$$

Additionally, if there is the need for a turntable motion (CTS spins along its middle point) the off-board laser secondary navigation will be a better choice to support that motion, with the CTS coming out of the physical path and turning until the magnetic field or the painted line are detected again.

The ability to enter the lift can be achieved using the dual methodology. In case the CTS is using the inductive guidance in the first part of a mission approaching the lift, a transponder installed close to the lift will switch navigation to optical guidance. The CTS will progress, regardless of the gap between the floor of the facility and the lift entrance, towards the painted or taped line in the floor of the lift.

In certain areas, such as the HCB, it could be envisaged to have only one of these two physical path methodologies installed at the floor level and/or to have only a few paths served by a physical path (either wire, painted line or both), and the remaining required paths supported by the secondary navigation system (virtual path) strongly reducing the number of wire/line to be implemented and keeping complete flexibility for changes.

The network of transponders to be installed on the floor is the same for both physical navigation methodologies in case the buried wire and the tape define the same physical path or a similar one. The RFID readers on the CTS serve both inductive and optical guidance. During a mission, the instruction given by a particular transponder can initiate switching between navigation methodologies.

Large-scale modifications to designated routes in particular areas can be easily achieved by re-routing the painted or taped lines. This can be done without re-routing the buried induction wire. If only the painted line is installed for new or highly modified paths, the integration back to the existing path network raises no problem, provided continuity on the common points and continuity on the path derivative are guaranteed.

The integrity of the painted or taped line cannot be checked remotely unlike the buried wire that can be checked by monitoring the conductivity of the wire. However, if the painted or taped line is on top of or close to the buried wire, the on board cameras can be used to stream images of the lines back to the operators. For this to happen, it is necessary to engage the induction wire system for CTS navigation, freeing up the cameras for the purpose of inspection only.

To implement this solution in the buildings, we propose 2 steps:

- Step 1: during the non-nuclear phase, only the painted or taped lines are implemented to test and validate all the trajectories inside the buildings. This can be done quickly and cheaply, without any intrusive/destructive work to the facility structure. Once the routes/ trajectories have been verified, testing of the induction wire (Step 2) can begin.
- Step 2: After the end of the trajectory/route tests, the tape or painted line will be removed, the wire will be set into the facility floor, and testing on the wire guidance technology will occur. There are no problems on positioning the wire during the commissioning (see Section 3.2.1.1). Afterwards the painted or taped line will be installed on top of the wire.

Table 3
Brief comparison of inductive and optical guidance.

Primary navigation	Solution 1: Wire/inductive	Solution 2: Optical
Ease to lay	Low	High
Flexibility to changes	Low	Medium
Physical robustness to damages with on top loads	High	Low
Passive	No	Yes
Dirt Immune	Yes	No
Invisible	Yes	No
Ease to cope with cross-roads	High	Medium
Potential electromagnetic confinement problems	Yes	No

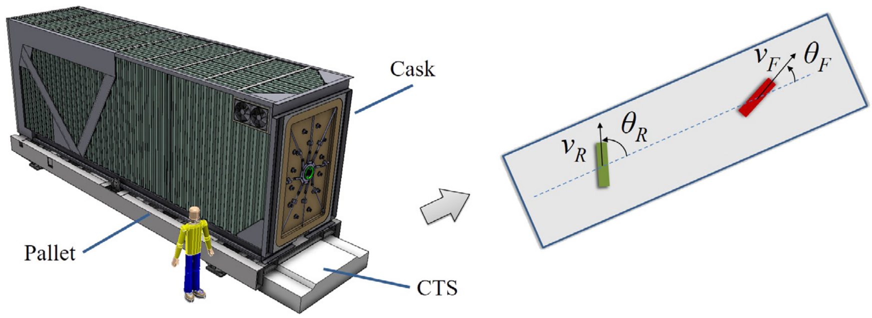

Fig. 11. CAD model of the vehicle and the respective kinematic model.

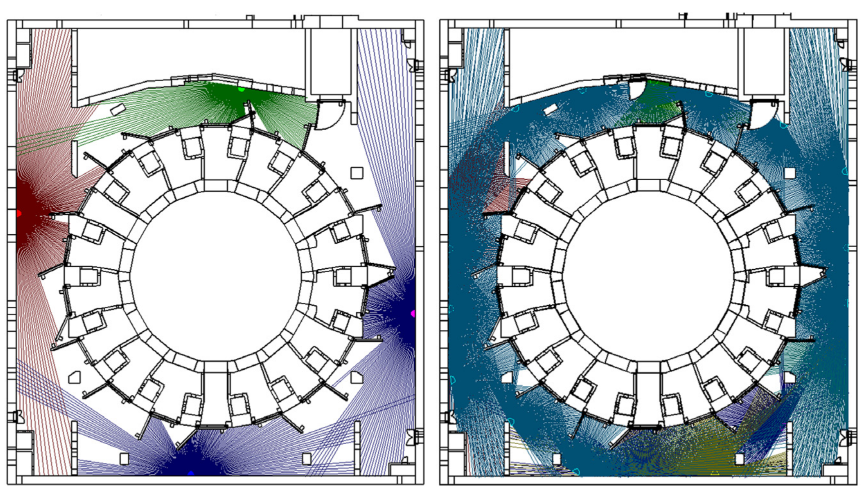

Fig. 12. Optimized lasers distribution along the walls of the level B1 of the reactor building in ITER and assuming the worst (fictitious) situation where all doors are opened: 4 lasers, 85% of coverage and low level of redundancy (left image) and 18 lasers, 99% of coverage and high level of redundancy, yields 5 lasers observing the CTS simultaneously anywhere (right image).

3.2.1.4. Secondary — solution 1, solution 2, solution 1+2 — lasers off-board. The secondary navigation methodology relies on off-board lasers installed within the TB and HCB. This is a minimally invasive technology capable of supporting the CTS navigation system. This methodology comprises a network of lasers installed on the walls of the galleries that interact with passive markers on the CTS. The position and orientation of each laser is optimized to maximize the area coverage of each laser in which the CTS might operate, and the number of overlaps between lasers. The latter in particular increases the amount of redundancy in the system, as it minimizes the number of "blind spots" if one laser was to fail. Computer-aided design (CAD) models of the buildings will be used to identify the optimal locations for the lasers. The Fig. 12 illustrates the optimized distribution of a set of 4 lasers (first image) and 18 lasers (second image) in level B1, the basement level of TB in ITER.

Off-board lasers require minimal infrastructure within the buildings: a physical support, power and communication lines. All off-board lasers are connected by wire to a central control room. The data acquired by each laser within the vicinity of the CTS is consolidated and interpreted, taking into account the position and orientation of each laser. The processed data output is equivalent to a 2D CAD model that is updated in real time.

The location of the CTS and other objects captured in consecutive time frames by the lasers can be continuously compared with the original CAD models. Any differences identified can determine the direction of CTS motion, doors aperture movements and other modifications to the local environment. In terms of guidance, navigation and control, the localization of the CTS can be accomplished by analyzing the differences between the position of the CTS in consecutive instants of time and compare these with the layout of the CTS. To improve the performance of the localization process, passive reflective markers are installed on the corners and on sides of the CTS to facilitate detection by the lasers. The positions and orientations of the lasers installed on the environment and the positions of the markers installed along the CTS are known. Based on the angles along which the lasers detect markers on the CTS it is possible, by triangulation, to estimate the localization of the CTS. Off-board lasers do not require recalibration after a power outage. However, the network of lasers installed on the walls can be remotely checked and calibrated without human intervention if necessary. Software to compute the localization using triangulation and markers and also for calibration are available in COTS.

In terms of radiation exposure, the components of a laser sensor most sensitive to exposure are the semiconductors. However, each laser is easily replaceable. To mitigate this problem, the off-board lasers can be shielded or even removed during the reactor operations to increase the lifetime of the sensors and to reduce the frequency of replacement.

The laser technology has a maturity of, at least, 25 years and is largely used by AGV in industry. The most used laser models in industry have a maximum range of 80 m, which covers the dimensions of the TB and HCB.

The off-board lasers have direct communication with the RH control room, where the localization is estimated without communication with the CTS, assuming no usage of the odometric information (estimate of the CTS position relative to a starting location). The accuracy of the laser-based localization can be improved by implementing a dead-reckoning technique that is generated by the CTS via a wireless communication system to the RH control room.

The coverage redundancy is adjusted according to the number of laser sensors. Assuming one laser sensor in front of each port (18 lasers per level), the coverage is approximately 100% and the coverage redundancy is 5 lasers in any place. Assuming only four laser sensors strategically placed in each level, the coverage is larger than 85% (the doors are not opened) and with a coverage redundancy of 2 lasers only in same places.

For precise docking in ports and in the lift, extra range sensors on-board the CTS are required, such as ultrasound sensors, lasers and photocells. These techniques can also be used for obstacle detection. On-board lasers (in front and rear sides of the CTS) are required if there is no other technology for docking. And, as the CTS will have on-board lasers for obstacle detection, these can be used to complement the off-boards laser for precise docking to the port and entering in the lift.

The estimated absolute localization of any vehicle (CTS or other) will be established through the generated data acquired by the off-board lasers. These are transmitted to the VR system and will help operators monitor CTS motion and control any other vehicle requiring deployment.

The secondary navigation has the following pros and cons:

Pros

- Absolute localization (accuracy of localization ±2 cm, which can be improved using odometers);
- Good range (>80 m);
- High coverage redundancy (adjusted according to the number of lasers installed on the scenario and the combination with off-board and on-board lasers);
- Flexible to follow a non-nominal path;
- Supports the motion of all rescue operations, in particular of the rescue vehicle;
- Minor intrusive installation work required within the facility (requires physical support, power and wire communication on walls);
- Use of COTS (hardware and software);
- Supports collision detection (by on-board lasers, the communication can be direct to the drive wheels; by the off-board lasers, the risk of collision identified through processing at the RH control room and a motion command, e.g., emergency stop, is sent to the CTS);
- No issues on docking/entering the lift; on-board sensors (such as ultrasound sensors, lasers and photocells) can be used individually or combined for docking/entering in the lift;
- Localization updated rate <0.1 s;
- Maturity >25 years, largely used by AGV in industry;
- Off-board lasers do not require recalibration after a power outage.

Cons:

- No built-in emergency stop; and
- Medium bandwidth for communication (wireless for on-board lasers, off-board laser shall communicate by wire).

The required sensors/equipment to be installed on the environment (TB) are the following. At least 4 lasers in each floor (coverage of 100% and coverage redundancy between 0 and 2 lasers in simultaneous in any place). To increase the coverage redundancy, more lasers are required. Power supply and wire communication on walls and odometers on the wheels.

3.2.2. *Solution 3 and solution 4*

Primary for solution 3	=	Lasers off-board
Primary for solution 4	=	Lasers on-board
Secondary for 3 and 4	=	Motion capture system

3.2.2.1. Primary solution 3—lasers off-board. This design variant is similar to Solution 1, and experiences the same operational issues. Please refer to the output of the review of Solution 1 as presented in Section 3.2.1.4.

3.2.2.2. Primary solution 4—lasers on-board. This primary navigation methodology relies on on-board lasers, i.e. laser in front, rear and possibly in lateral sides of the CTS, and passive markers within the facility at pre-defined locations.

The localization of the CTS uses passive reflective markers positioned around the facility that are detected by the on-board lasers. The triangulation base technique evaluates the position and orientation of the CTS using the angles with which the markers are detected, theirs positioning in the CAD model of the facility and the information from the odometers on the CTS wheels. This position and orientation data is transmitted to the central control room where it is processed to generate references to the virtual path to follow that are sent back to the CTS.

Each laser is located on the CTS in such a way that it is easily replaceable. On-board lasers do not require recalibration after a power outage. The laser on-board used for navigation purposes also provides data for obstacle detection. The inclusion of extra sensors on-board (ultrasound or additional lasers for example) can be considered to provide redundancy in the obstacle detection approach.

Pros:

- Absolute localization (accuracy of localization ±2 cm, which can be improved using odometers; possible not so good as the combination with off-board lasers);
- Good range (>80 m);
- Flexible to follow new or revised paths, and supports all rescue operations as it can be readily applied to new/additional rescue vehicles;
- No intervention in the scenario;
- Use of COTS (hardware and software);
- Support collision detection;
- No issues on docking/entering the lift (the on-board lasers can be used individually or combined with other sensors for docking/entering in the lift);
- Localization updated rate <0.1 s;
- Maturity >25 years, largely used by AGV in industry; and
- On-board lasers do not require recalibration after a power outage.

Cons:

- No redundancy (the only possible redundancy is to include two lasers in front and two other lasers in the rear of the CTS);
- Requires more passive markers within the facility (not only in the entrances to the ports, but along the galleries);
- No built-in emergency stop; and
- Medium bandwidth for communication (wireless for on-board lasers, since the off-board laser shall communicate by wire).

The required sensors/equipment, to be installed in the CTS or in the environment (TB) are: 2 lasers as a minimum (1 in front and 1 in rear, with potential for additional lasers to be added to the sides) and passive reflective markers.

3.2.2.3. Secondary — solutions 3 and 4 — motion capture system. A set of markers is attached to specific points in the CTS. These markers can be either passive, such as infrared (IR) reflectors),or active (with self-illumination). The specific locations of these markers define a unique identification of the CTS. An assembly of special purpose cameras is installed in the facility in such a way that, for any possible CTS position, each marker is visible by at least 3 of these cameras. Each camera device contains a strobe IR light emitter that allows robust detection and location of the markers. All cameras are connected to a central server that collects localization data streamed from them. The system provides sub-millimeter absolute identification and localization of each CTS, anywhere in the Tokamak and HCB. This can be achieved at rates with an order of magnitude of 100 Hz, with ranges of about 30 m. Before being capable to operate, the system has to be calibrated. The calibration procedure involves manually moving a set of markers attached to a rigid structure over all areas covered by the cameras.

Motion capture is a mature technology used mostly in precise human body posture tracking and the monitoring of aerial, terrestrial and ocean-based unmanned vehicles. Moreover, the technique is applied in several industrial applications. There are several manufacturers that can provide competitive systems, thus making motion capture systems mature COTS items. However, rapid advances in camera technology may result in technologies originally installed in the reactor facility becoming obsolete before the end of the facility's operational life. As a result, it may be more difficult to obtain spare parts or entire replacements as the equipment ages and requires repair.

For nominal operations, the motion capture system serves as a redundant navigation system. Virtual trajectories for the CTS are followed by a guidance system, as in the case of the off-board lasers. Special care has to be taken when considering entering/leaving the port, as well as entering/leaving the lift, since a minimum amount of markers have to be visible by at least three cameras in order to guarantee precise detection, identification, localization, and tracking in these situations.

For rescue operations, the motion capture system allows localization of the CTS anywhere in the facility, even outside of nominal operational locations, as long as a minimum amount of markers are visible by at least three cameras.

The motion capture system requires the installation of a potentially large amount of cameras, connected over a network with a central server. This implies a large amount of cabling through the building infrastructure. Radiation exposure is also an issue since these cameras contain sensitive electronic equipment, and the camera lens cannot be easily shielded without obscuring or limiting their range of vision. A possible solution to mitigate this problem is to install the cameras only during maintenance periods. However, this may require an extended period of manned access to the facility so that the cameras can be recalibrated.

Pros:

- Very accurate absolute localization (accuracy of localization <1 mm);
- Redundancy (redundancy is adjusted according to the density of cameras intended to install on the scenario);
- Flexible to follow a non-nominal or revised path and supports all rescue operations by enabling the remote control of rescue vehicles;
- Minor intrusive works to the facility (requires physical support, power and wire communication on walls);
- Use of COTS (hardware and software);
- Support collision detection (indirectly, that is, by matching the vehicle volume at the estimated position with the map);
- No issues on docking/entering the lift (provided enough camera coverage);
- Very high localization updated rate (typically 100 Hz); and
- Maturity >10 years, largely used for capturing motion of small bodies.

Cons:

- Limited range (<30 m);
- No built-in communication neither emergency stop;
- Expensive given the number of expected cameras at each floor;
- No experience in industrial environments with heavy load vehicles;
- Requires an extensive amount of cabling to route the cameras to the central facility; and
- Cameras are sensitive to radiation exposure.

The required equipment are: approximately 40–50 cameras in each floor (2 in front of each port and 12 spread along the galleries), power supply and wire communication on walls, and passive or active markers on CTS.

3.2.3. Solution 5 and solution 6

Primary for solution 5	=	Magnetic-gyro grid navigation
Primary for solution 6	=	Lasers on-board
Secondary for 5 and 6	=	Lasers off-board

3.2.3.1. Primary solution 5—magnetic-gyro grid navigation. In this solution, a regular grid of magnets is installed on the floor, aiming at covering the entire surface of the area where the CTS can move.

The magnets are rare earth type and normally 10 mm in diameter and 15 mm long. They are installed in a grid pattern, seated in a drilled hole in the floor and covered with epoxy giving a smooth and flat floor surface. The CTS is equipped with magnet sensor(s) that detects the magnetic field of a magnet and gives information about the vehicle position, and updates the odometer distance counting as the magnets are passed. Each magnet in the grid is used to calibrate odometry.

Unlike transponders that have their own code, which provides unique localization data, magnets are indistinguishable from each other. If a magnet is missed along the virtual path defined for the mission, the CTS location error will increase because the length of the path performed in free-roaming will be longer. For this reason usually a maximum distance or allowed amount of magnets to be missed is defined, which can differ based on the characteristics and requirements of the application. Motion control can take this aspect into account and issue and emergency stop if an expected magnet is not detected.

Usually a pair of magnets for every five to ten meters is required for AGVs in industrial applications. However, optimized spacing will have to be calculated for this project. The magnet network has to be designed according to the trajectories that the CTS has to follow in such a way that a magnet must be always detected before the position and orientation errors become larger than a given threshold.

For further orientation accuracy, a rate-gyro unit can also be installed on the CTS, providing CTS heading data relative to a calibration location. Rate-gyros are known to have bias drift that increases with time, even when the vehicle is not moving. The rate-gyros require periodic calibration due to the drift. This calibration may be provided by the magnets (if their magnetic fields are equally aligned) or in known locations, e.g., ports, and in battery charging locations.

Pros:

- No physical path;
- Flexible for changes on the path (the same magnets can be used for different paths; additional magnets can be installed on the floor in case of the new paths are beyond the area covered by the available magnets);
- Sustainability (availability of spare parts or replacements during the reactor lifetime);
- Support rescue operations partially;
- No issues entering the lift;
- Absolute localization estimation providing all magnets on the route are detected; and
- Mature technology.

Cons:

- Moderate amount of intrusive work within the facility for installation (magnets need to be set in holes dug out in the floor);
- Errors on absolute localization (there is a risk of cumulative errors);
- Drift on the gyroscope (requires periodic calibration);
- Odometers accumulate localization errors between two magnets;
- If one magnet is missed, errors will increase;
- Maintainability (replacement is difficult during the reactor lifetime, even if parts are available);
- No built-in communication nor built-in emergency stop; and
- After a power shut-down the CTS has no absolute localization.

The required equipment is: magnets spread along the floor in each level, magnet sensors in the CTS, odometers in the CTS, and Rate-Gyroscope in the CTS.

3.2.3.2. Primary solution 6—lasers on-board. This option is similar to Solution 4, and performs similarly well. Please refer to the discussions in Section 3.2.2.2 for further information.

This solution relies only on laser technology, both for primary (lasers on-board) and for secondary navigation (lasers off-board). An alternative solution will be to adopt laser off-board for primary navigation and laser on-board for secondary. However, for safety reasons, the best option is to have the navigation sensors on-board to provide data immediately to the on-board control system without relying on the wireless communication system.

3.2.3.3. Secondary solution 5 and solution 6—lasers off-board. The same considerations as for the secondary navigation in Solution 1 and 2 described in Section 3.2.1.4.

4. Robustness and integrity issues

4.1. Radiation

The proposed solutions are based on combinations of software and hardware. The software runs in a computer installed on the RH control room or in the CTS on-board computer. The hardware is the set of equipment and sensors installed on the CTS, and on the galleries, e.g., the off-board sensors and transponders.

The off-board sensors, if permanently installed in the galleries, are exposed to the radiation effects during the reactor operations and during the remote maintenance operations. The on-board sensors installed on the CTS are exposed to radiation effects mainly during the transportation of activated loads and when accessing a port to return or take a load.

The radiation effects on the sensors dedicated to navigation considers the type of materials, the damage threshold of radiation supported by each material and the maximum expected lifetime. The damage threshold considered for a sensor is the value taken from the sensor component that is most sensitive to radiation (i.e. the component that has the lowest radiation threshold).

The sensors comprise an envelope usually made by plastic or a thinner metallic box, electronic components, plugs and cables. The most sensitive component of a sensor is the semiconductor, which has a damage threshold of 100 Gy, [16]. This is common to all sensors identified in the proposed navigation solutions.

In Solution 1, the guiding wire installed on the floor has conductors, sheath and insulators. The most critical part may be the insulators that will be in place over the entire lifetime of ITER. They are unlikely to require periodic replacement. The frequency generator in Solution 1 uses semiconductors that may require replacement approximately every 6 years. The RFID transponders installed on the floor are made of semiconductors. This will not endure over the entire lifetime of ITER, and will therefore require periodic replacement. However, the RFID transponders are easily replaceable.

The steering antennae installed on the CTS which are used to follow the induction wire, or the RFID readers, will likely operate for the 2000 h.

The off-board lasers proposed as secondary systems in solutions 1, 2 and 6, and primary system in Solution 3 only support 100 h of operations, falling significantly short of the 2000 h. However, the off-board lasers are easily replaceable: the sensors are detachable from walls and can be unplugged from power and communication cables in a short period of time. To reduce the radiation effects outside of maintenance operations, the off-board sensors shall be shielded or removed, if possible.

The on-board sensors, which are proposed in all solutions, are built with semiconductors and hence are only capable of supporting a maximum of 100 h of operations. The frequency of replacement can be decreased shielding the on-board sensors or installing the electronic parts remotely. Similar to the off-board sensors, the on-board sensors are easily replaceable.

In summary, Solution 1 is the best in terms of radiation exposure. This is because it utilizes the more robust induction wire and antennae configuration which can largely support the minimum requirement of 2000 h operational life. The only operational issue is that it relies on the use of transponders that must be periodically replaced. However, the transponders are very cheap COTS devices easily to be replaceable.

Solution 2 is very similar to Solution 1 in terms of the approach (primary and secondary, i.e., physical path + virtual path) and in terms of radiation exposure. In Solution 2, the optical lines on the floor are as robust as wires when considering radiation effects, but the cameras installed below the CTS are more sensitive to radiation when compared with the antennas of Solution 1. The cameras must be also replaced periodically, but this can be easily achieved. Solution 1 + 2 shares the pros and cons of Solution 1 and Solution 2, with the transponders and the cameras not satisfying the falling short of the 2000 h, but being easily replaced.

Solution 5 utilizes solutions that use virtual paths only. It performs similarly to Solution 1 in terms of its robustness to radiation exposure. The magnetic grid is the most sensitive component that must be replaced periodically to ensure functionality. However, it is more difficult to replace, since there are more magnets along the floor.

Solutions 3, 4 and 6 perform equally with regard to their resistance to radiation exposure. This is because these solutions all use lasers and motion capture systems only. These units are totally dependent on semiconductors, which are highly sensitive to radiation exposures. As a result, they will require periodic replacement.

4.2. Environmental conditions

With regard to options using induction wire guidance, the induction wires connected to the frequency generator and transponders are immune to effects of variations in temperature, humidity, pressure, light and dust on the galleries. This is because they are installed under the floor of the building and are therefore isolated from the local environment.

With regard to the optical navigation system, the taped or painted lines are immune to residual magnetic fields, temperature, humidity and pressure. The risk of possible damage to the lines is also greater from repetitive movement of vehicles over the top of them, relative to other potential factors such as exposure to dust. Since the cameras are installed under the CTS and therefore shadowed by it, it is necessary to provide light through the installation of LED. As a result, the cameras are independent of local light conditions within the building. There is a risk that dust will settle on the lens of a camera, which may impair its function. This can be monitored by checking the quality of images generated by the cameras.

The on-board and off-board lasers of the virtual systems are immune to residual magnetic fields and lights. In addition, the COTS laser sensors are designed for use in ambient indoor temperatures and pressures. Some sensors are resistant to humidity and dust, according to the IP67 standards (International Protection Marking, IEC standard 60529).

The MOCAP system is immune to residual magnetic fields. It is designed to work in ambient indoor temperatures, humidity and pressures. The lighting levels must be calibrated and controlled for the best performance of the MOCAP navigation system. This is also applicable to the quantity of airborne dusts in the facility, although to a lesser extent.

5. Trade-off

5.1. Trade-off criteria

The identified solutions were assessed against five trade-off criteria as listed below, to fully take into account the anticipated performance requirements for the navigation of the CTS. The choice of the proposed solution is supported by scores, which were allocated to the options that reflected their performance against each of the trade-off criteria. Weightings to reflect the importance of each of the trade-off criteria were also allocated. The weightings were based on assumptions made on the likely expectations of a reactor facility and their concerns. There is potential to assess the options against additional trade-off criteria, utilizing the same approach.

The technical feasibility is the most important criterion against which the options should be assessed. The robustness of the technologies, with particular regard to sensitivity to radiation, is the second important criterion. The "CAPEX/OPEX Cost" (capital expenditures and operating expenses), "Replacement Ability" and the "Percentage of COTS in the Navigation Solution" are also considered criteria, with all three allocated the same weight. For each criterion, a set of topics as listed below, is taken into account. They are listed by decreasing order of importance, with those with the same importance grouped in the same cell.

- Technical feasibility
  - Safety for navigation (emergency stop);
  - Flexibility to change the nominal operations;
  - Rescue ability and recoverability;
  - Diversity of technologies;
  - Accuracy of absolute localization, i.e., the (x, y, θ) in the referential of the building;
  - Relative localization to the path;
  - Operational complexity for entering in the lift (overcoming the gap); and
  - Maturity in industrial environment.
- Robustness (radiation, temperature and availability)
  - Radiation sensitivity;
  - Operation within a residual magnetic field of up to 1 mT;
  - Operation close to metal on the floor;
  - Impact with the exposure during the Tokamak operations (outside of the maintenance operations);
  - Sensor redundancy; and
  - Integrity checking.
- Cost CAPEX and OPEX/costs of operation
  - CAPEX on environment (sensors installation, as lasers or cameras on the walls and wires or tapes on the floor);
  - CAPEX on CTS;
  - OPEX on environment (energy, communication and computation); and
  - OPEX on CTS (energy, communication and computation).
- Replacement ability
  - Level of difficulty to replace according to;
  - Number of replacements expected during the reactor lifetime; and
  - Sustainability (availability on the market).
- Use of COTS
  - Percentage of COTS in the navigation solution.

The trade-off analysis is performed for each solution that comprises a pair of a primary and a secondary navigation methodology. This means that the assessment of each criterion is not done individually for each particular methodology, but for each studied pair of primary and secondary navigation methodologies.

5.2. Trade-off evaluation

The Table 4 presents the assessment of the each navigation solution relative to the requirements directly related with navigation. The total score for each solution is evaluated as follows:

$$S(k) = \sum_i w_i \cdot \left[\frac{\sum_l p_{il} \cdot s_{il}(k)}{\sum_l p_{il}} \right] \quad (2)$$

where:

- $S(k)$ is the total score of the solution k.
- w_i is the weight for the criteria i (e.g., technical feasibility, robustness, cost CAPEX/OPEX, replacement ability and use of COTS).
- p_{il} is the weight for the sub-criteria l of criteria i (e.g., sub-criteria "safety for navigation" of criteria "technical feasibility").
- $s_{il}(k)$ is the score of the solution k in the sub-criteria l, of criteria i, with the possible values 1 (poor), 2 (fair), 3 (good) and 4 (very-good).

Table 4
Trade-off evaluation.

Criteria	Weight	Solution 1	Solution 2	**Solution 1 + 2**	Solution 3	Solution 4	Solution 5	Solution 6
Technical feasibility	40	3.1	3.0	3.4	2.6	2.9	2.4	3.0
Robustness	30	2.9	2.9	2.9	2.9	2.7	2.3	2.9
Cost CAPEX/OPEX	10	3.3	3.0	2.8	2.8	2.3	2.5	3.8
Replacement ability	10	3.0	2.7	3.0	2.0	2.0	2.7	3.0
Use of COTS	10	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Total	100	303	292	**311**	265	269	246	303

5.3. *Proposed solution*

Solutions 1, 2 and 1 + 2 are the only solutions that combine primary and secondary systems using completely different technologies as discussed in Section 3.

Solution 1 + 2 is the highest scoring option overall. It retains the high safety performance of a physical navigation system, and the flexibility to accommodate path changes and the lift gap with the use of painted or taped lines. Moreover, this option enables the equipment of the CTS with both steering antennae and cameras allowing operators to switch between primary navigation methodologies (i.e. inductive wire and optical navigation). Both types of sensors (steering antennas and cameras) are COTS, cheap and available for the lifetime of reactor. This option also gains from a range of other benefits identified for the application of Solutions 1 and 2 singularly. The installation of the painted or taped lines and wires will be performed in two different steps following the procedure described in Section 3.2.1.3.

Solution 1 has the second best score since it includes the wire navigation. This offers strong nuclear safety characteristics, a high level of maturity, is highly reliable, is well used in industry and has a built-in emergency stop. However, it presents some drawbacks, as there is no flexibility for changes in the paths use for nominal operations. The requirement for the installation of long wires and cables, as well as potential restrictions on the height of the antennae may make implementation of this option alone more complex, impairing the performance of this option.

The Solution 2 has received the third highest score. It avoids the main operational problem of Solution 1 in terms of any possible perturbation from the steel-grid on the ground. It also introduces the flexibility required to accommodate changes to the nominal paths taken by the vehicles, as it is easier to remove and paint or tape a new line than re-route wires laid in the facility floor. However, this technique is not so commonly used in industry. Further, to be practicable it would be necessary to source cameras on the CTS that are more sensible to radiation exposure. Finally, it was recognized that the consecutive motion of the CTS on top of painted or taped lines may degrade them easily.

The three solutions referred to above share the off-board lasers for secondary navigation, this providing localization of the CTS in its motion and well as for any other vehicle (e.g., rescue vehicle) that should move in the environment of a fusion facility.

The remaining solutions (3 to 6) only use the concept of virtual path, thus providing full flexibility for changing nominal paths and to support any required path for rescue operations. The solutions 3, 4 and 5 use different technologies for primary and secondary navigation, while Solution 6 uses the same type of technology (laser-based) for primary and secondary, even though with diverse methodologies.

The Solution 3 when compared with Solution 4 offers a better redundancy system, since the off-board lasers can do the same job as the motion capture system. In Solution 3, the primary and secondary are very similar and they are exchangeable. However, the Solution 3 becomes more expensive in terms of hardware and software when compared to Solution 4. In Solution 5, the primary is based on a technology of dead reckoning between consecutive magnetos that requires the permanent supervision of the secondary, otherwise it becomes a risky solution. Hence, the Solution 5 offers a very low level of redundancy which is immediately withdrawn.

According to the trade-off criteria presented in Section 5.1 the solutions are sorted as follows: solutions 1 + 2, 1 and 6 (equally placed), 2, 4, 3 and 5. The Solution 5 is withdrawn given its very low level of redundancy. In case of incompatibility with the metal on the floor, the Solution 1 is withdrawn. In case of rising the importance of flexibility, the solutions 1 and 2 are outdated by the solutions with virtual paths. In that case, the Solution 3 is the best solution in terms of redundancy. Solution 4 is a downgrade of Solution 3 removing the off-board lasers, while the Solution 6 removes the motion capture system. Given the maturity of technologies, cost, COTS and reliability, Solution 6 is better when compared with Solution 4.

In summary, the best proposed solution is Solution 1 + 2 for combining physical and virtual paths closely followed by Solution 6 that relies only on laser technology.

6. Conclusions

This paper presents a both qualitative and quantitative evaluation of several navigation solutions targeting AGV in nuclear fusion power plants, with particular emphasis on the ITER case. Each one of these solution includes two different navigation technologies, termed primary and secondary. Primary assures nominal operation, focusing on robustness, while secondary assures both nominal and non-nominal operation, focusing on flexibility.

The selected solution, denoted Solution 1 + 2 and supported by the trade-off analysis presented in Section 5 is self-sufficient to support all nominal operations, thus offering redundancy among them. Non-nominal operations, including both recovery from minor navigation failures and rescue operations, are supported by the secondary system. In addition, each one of the primary and secondary provide redundancy, such that individual sub-system failure does not compromise navigation. It should also be noted that in total three different technologies are being used – inductive, optical, and laser — thus contributing to resilience to unexpected failures and long-term sustainability of the navigation system.

The primary navigation system is based on a physical path, that is, the CTS motion is guided by a path physically installed on the environment. Two different technologies are used to define the paths: wire guidance and optical line guidance. Wire guidance, explained in detail in Section 3.1.1.1, comprises a wire buried on the floor, where a modulated current flows; this current generates a magnetic field sensed by a pair of coils on the vehicle, allowing the measurement of the deviation with respect to the path. This deviation is used to steer the vehicle. Optical line guidance, explained in detail in Section 3.1.1.2, follows the same general principal, but uses a painted line on the floor to specify the path, and a special purpose video camera on-board the vehicle. The use of these two distinct technologies provides, besides additional redundancy, two complementary features: on the one hand, since painted lines can be easily modified, they allow for (1) testing and validation of the trajectories during commissioning (non-radiation phase), where any unexpected issue can be easily fixed and re-evaluated, and (2) flexibility to quickly deploy new paths, and on the other, once the paths are tested and validated, they can be replaced by buried wires, which are more resistant to wear due to wheel friction on the floor. Any potential problem on the wire guidance due to the metal structure of the ground can be mitigated by properly defining the height of the steering antennas on the CTS.

The secondary navigation system is based on a virtual path, that is, the paths are defined on a computer and the CTS motion is guided by an absolute localization system that steers the vehicle in order to follow the defined path, as described in Section 3.1.2. The absolute localization system comprises an off-board network of laser range finder sensors installed on the walls that detect a set of passive reflective markers on the CTS. This network of sensors is required to cover the whole operational scenario (TB and HCB) with a degree of redundancy, such that individual sensor failure does not hinder localization. However, in specific locations, namely inside the ports and the lift, additional sensors are necessary to complement localization; these are on-board laser range finder and sonar sensors. The secondary system both supports nominal and non-nominal (recovery and rescue) operations, since it is able to localize the CTS at all times.

In addition to this selected solution described above and according to the trade-off analysis presented in Section 5, the second best solution is proposed, denoted as Solution 6: a virtual path solution, thus capable of both nominal and non-nominal operations, using off-board and on-board laser range finder sensors. The off-board sensors localize the vehicle as explained above, while the on-board ones use markers on the building wall to do so. Each one of the off-board and on-board set of sensors are individually capable of localizing the CTS at all times. Both the selected solution and the second best employ an off-board network of laser range finder sensors. These sensors can be used to localize the CTS, as explained, as well as any other object on the environment, e.g., a rescue vehicle, provided that passive markers are installed in specific locations along the object sides.

The evaluation presented in this paper can be addressed for the development and supply of transport systems not only in upcoming fusion facilities, but also in the current or new fission facilities. In addition, the conclusions are important not only for the design of the vehicle, but also for the requirement specifications of the buildings to support the navigation in nominal, recovery and rescue operations. The main challenges are shielding the sensors and install the electronic devices remotely. New technologies applicable for the mobile robots navigation are coming. However, unless a radical change occurs in the navigation sensors, the technologies addressed in this paper will keep working in a long term, i.e., during the lifetime of the next reactors.

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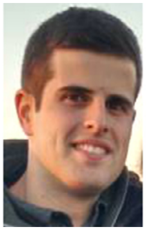

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