Mobile Robot Navigation for Remote Handling operations in ITER

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***Abstract*— This paper briefly summarizes the work related with mobile robotics developed by IST on the field of remote handling operations to be carried out in the International Thermonuclear Experimental Reactor (ITER) by a transfer casks system. The transport operations of contaminated and heavy loads inside ITER buildings requires optimized trajectories. Approaches of path planning and trajectory optimization based on geometric constrains and also based on rigid body dynamics were studied and tested in the cluttered scenarios of ITER. The localization problem of mobile robots was also addressed, with a novel approach of using an optimized sensor network installed on the scenario with probabilistic algorithms to estimate, in real time, the pose of a vehicle, or a set of vehicles, operating in the scenario. The navigation is also considered with three modes of operation: automatic, semi-automatic and manual. Virtual Reality Systems and Human Machine Interfaces are under development. A summary of results achieved so far are presented in the paper.**

I. INTRODUCTION

The ITER (International Thermonuclear Experimental Reactor) is a joint international research project aiming to demonstrate the technological feasibility of fusion power as an alternative and safe power source. During maintenance operations human presence will not be allowed in ITER's Tokamak Building (TB) and Hot Cell Building (HCB). Therefore, the setup of an effective ITER Remote Maintenance System (IRMS) is of vital importance to the project.

The transfer cask system, also known as Cask and Plug Remote Handling System (CPRHS), is the transport platform operating between the TB and the HCB, as shown in Figure 1. There are up to 9 different CPRHS configurations, each defined according to the required activity. The largest CPRHS has dimensions 8.5m x 2.62m x 3.62m (length, width, height) and is entrusted with the transportation of heavy loads (a total height with maximum load of 100T) and highly activated (gamma dose rates in excess of 100 Gy/h) components [4]. It comprises three sub-systems: a cask envelope containing the load, a pallet that supports the cask envelope, and the Cask Transfer System (CTS) that drives the entire CPRHS. Its kinematic configuration, first proposed in [5], endows it with the required flexibility to navigate autonomously or remotely controlled in the cluttered environments of the TB and the HCB.

During the reactor's operation, the in-vessel components, such as the blankets that cover the vacuum vessel, are expected to become activated by neutron exposure. When such components have to be transported to the HCB operations make use of the CPRHS, which is required to dock in pre-defined locations, e.g., the vacuum vessel port cells (VVPC), located on the three levels of TB: B1 (divertor level), L1 (equatorial level) and L2 (upper level). Due to the confined environment, maneuvers play an important role for entering/exiting the VVPCs and the lift connecting the TB and the HCB. Operations in the HCB include the diagnose and refurbishment or disposal as radwaste. Hence, the CPRHS must also dock at the docking stations through a Port Plug (PP) interface or park in the Parking Areas (PA) at different levels of the HCB (B2, B1, L1 and L3).

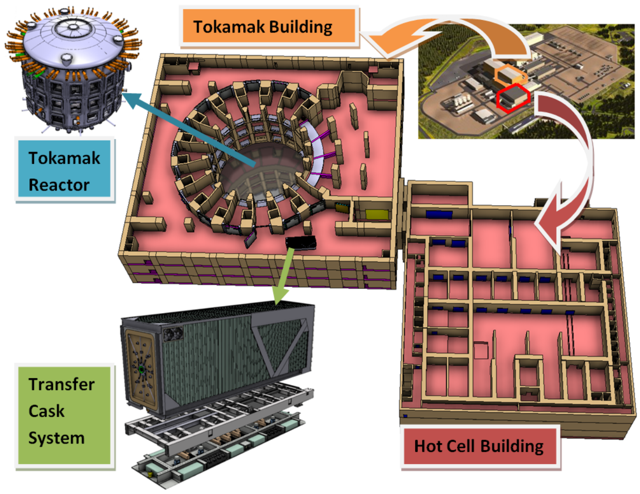

Fig. 1. The CAD models of TB and HCB scenario and the detailed views of the CPRHS, the reactor and the ITER site.

The transport operations of heavy and contaminated loads is an important key issue within remote handling since the beginning of ITER design. Since 1997, two research laboratories of Instituto Superior Técnico (IST), the Instituto for Systems and Robotics (ISR) and Instituto de Plasmas e Fusão Nuclear (IPFN), have been involved in ITER remote handling activities. In 1997 a conceptual study on flexible guidance and docking system was carried out. In 1998, IST studied the geometric feasibility of air cushion remote handling casks and extensions for free roaming navigation. The IST was the main contractor in both projects. Also, in 1998 IST collaborated with NNC Ltd and AeroGo on the design study for an air floating system. More recently, IST returned to the studies of trajectories optimization. In 2009 and 2010, several tasks were performed related to the studies of optimized trajectories and possible modifications in the buildings, development of Virtual Reality and Human Machine Interfaces, a Test Facility proposal and technical support, in collaboration with CIEMAT and ASTRIUM SAS. Since 2011 in collaboration with ASTRIUM ST and IST as the main contract, the algorithms for trajectory optimization have been improved with a new approach to be applied for all nominal operations, including parking and rescue missions in all levels of TB and HCB. Along these years, several scientific outputs have resulted, which are briefly summarized in this paper.

This paper is organized as follows. Section II describes the trajectory optimization approaches (common paths for both wheels, the inclusion of maneuvers and different path for each wheel) and presented simulated results. Section III describes the proposed approach to estimate the pose of vehicles, which includes the optimization of a sensor network and probabilistic algorithms for vehicle localization. Section IV describes the navigation modes and the related work already done. Finally, the Section V presents the main conclusions and the future work.

II. TRAJECTORIES OPTIMIZATION

Trajectory optimization evaluates the best trajectory (best path with the optimized velocity profile) in terms of the shortest distance and smoothness between the starting and target locations and the maximum distance to the closest obstacles along the journey. Depending on the navigation methodology that will be adopted for the CTS, the paths can be represented in two ways:

- **Real path** - a path physically defined at floor level (e.g., painted lines on the floor, strips wrapped on the floor, buried wires, buried track, etc).
- **Virtual path** - a path defined at computer level, and not physically defined in any part of the environment.

The CTS acts as a mobile robot and can move independently from the cask and pallet. This mobile platform was conceived with a rhombic configuration with one pair of drivable and steerable wheels positioned on the front and rear of the vehicle and two swivel wheels on the sides (see Figure 2, where a second pair is available for redundancy). This kinematic configuration was proposed in [5] to endow the transporter with an high maneuvering ability and flexibility, key traits when considering the cluttered nature of the ITER environments. Given the CTS kinematics, in what concerns path generation there are two possible situations, independent of the velocities: the same path for both wheels and different paths for each wheel (with a constraint between the paths, since the CTS is a rigid body).

A. Common path for both wheels

For a CPRHS safe motion, a path maximizing the distance to obstacles and minimizing the distance between the start and the goal poses (position and orientation) and the smoothness must be evaluated. By specifying the CPRHS

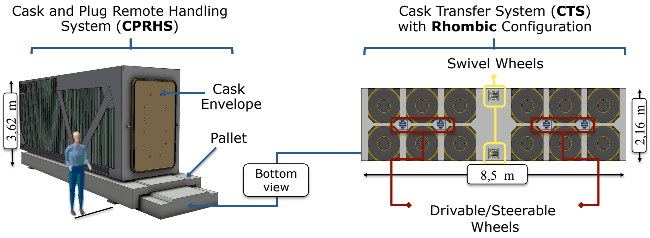

Fig. 2. Left: schematic view of the CPRHS. Right: the CTS with its rhombic configuration.

velocity along the path, the optimized trajectory is obtained. To meet these conditions a motion planning methodology was developed and implemented, [6]. It is achieved in four main steps, as displayed in Figure 3: 1) generation of a 2D map of the environment from its 3D model, 2) evaluation of a geometric path, 3) path optimization, and 4) building a trajectory from the optimized path. A description of each follows.

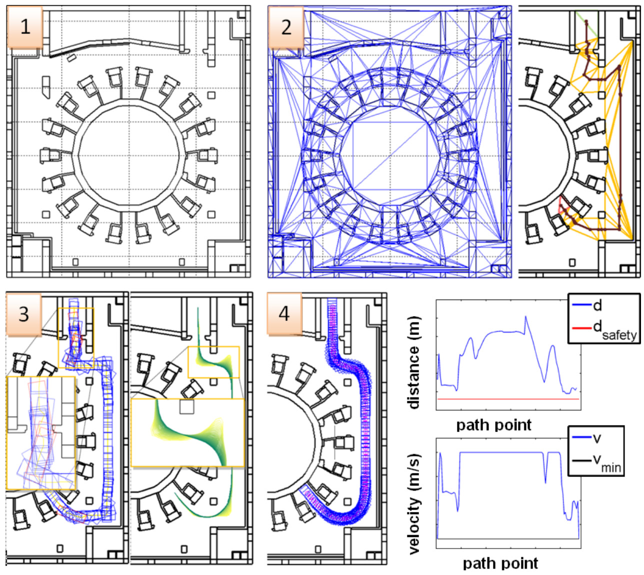

Fig. 3. Motion planning methodology. Step 1: generation of the 2D map of the environment. Step 2: evaluation of a geometric path. Step 3: path optimization. Step 4: final optimized trajectory, with the evolution of the distance to obstacles and velocity along the path.

Step 1: From 3D CAD models, a 2D representation is obtained by projection at floor level, including all the relevant elements that might conflict with the CPRHS volume. The TB and the HCB are well structured scenarios, whose footprint is a line segment and thus the 2D map can be considered as a set of line segments.

Step 2: Find a collision free geometric path, i.e., a set of 2D points that connects the start and goal points and do not intersect the line segments of the map. For that, the 2D map is decomposed into a set of triangles, a typical cell decomposition [8], [9], by using the Constrained Delaunay Triangulation (CDT), [10], to account for all walls. Afterwards, the algorithm determines all sets of sequences of triangles that contain and link the start and goal points.

Each sequence of triangles is then converted into a sequence of points (mid point of the common edge of two consecutive triangles) yielding a path. The shortest and feasible path is chosen as the geometric path (step 2 of Figure 3), acting as the initial condition for the path optimization module.

Step 3: The so obtained geometric path does not guarantee a collision free path for a rigid body, such as the CPRHS, as illustrated in the left image of step 3 of Figure 3 with a CPRHS in collision with the pillar, and thus may be unfeasible. To obtain an optimized path, two criteria are included in the algorithm: clearance from obstacles, by increasing the distance from the CPRHS to walls and path smoothness, entailing getting shorter and smoother paths without slacks. To address the referred issues, the optimization procedure uses the elastic band concept, [11], where the path is modeled as an elastic band, similar to a series of connected springs, subjected to two types of forces: internal and external forces. The first are the internal contraction forces, whose magnitude is proportional to the amplitude of displacement and determine that the paths becomes retracted and shorter. The repulsive forces are responsible for keeping the path, and consequently the vehicle, away from obstacles.

Step 4: To define the velocity of the CPRHS along each point of the optimized path, the CPRHS velocity is defined as a function of the distance to the nearest obstacle. When the distance is above a given threshold, a maximum allowable velocity for the CPRHS is assumed. To avoid the situation where the motors' torque is not sufficient to overcome friction, a minimum allowable velocity is considered for distances smaller than the minimum safety distance. Otherwise, the velocity varies linearly between minimum and maximum velocities.

There are particular situations where the described methodology fails to generate feasible solutions, due to the confined environment. The inclusion of maneuvers can greatly improve the path planning, by providing a feasible solution where none could be found before and also improve the level of safety by increase the distance to the closest obstacles along the trajectory.

B. *Inclusion of Maneuvers*

A maneuver exists when the CPRHS stops and changes its motion direction, so as to achieve a specified orientation. A maneuver requires splitting the path in two sub-paths with the constraint that the final pose of the first sub-path is the initial pose of the next sub-path. By taking advantage of the CPRHS kinematic configuration, the algorithm in [6], was improved to incorporate one or multiple maneuvers. In case n maneuvers are required, the path is divided in $n+1$ sub-paths and the path optimization is applied to each. The decision of including maneuvers is taken when a path without maneuver is not feasible, as illustrated in Figure 4-a) with a collision in red, or does not fulfill the minimum safety distance to obstacles. The algorithm at this actual stage requires for any point(s) of maneuver to be introduced manually and adjusting its position(s) during the optimization to obtain the final trajectory, as displayed in Figure 4 b).

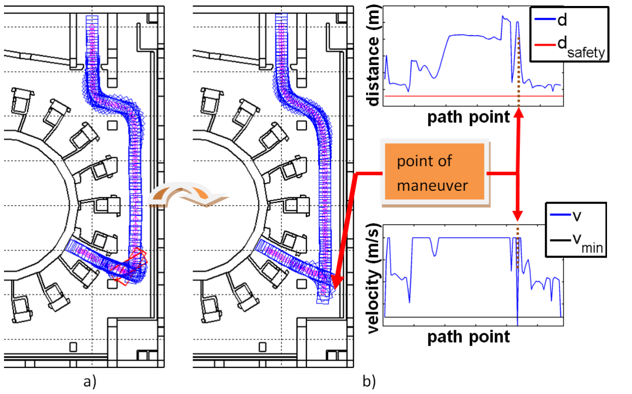

Fig. 4. Example for VVPC 17 in level B1 of TB: a) trajectory without maneuver, with collision (red); b) optimized trajectory with maneuver, minimum distance to obstacles and velocity along the path.

C. *Different path for each wheel*

The previous algorithm provides a common path for both wheels, which can not take the most benefit of the rhombic like configuration. In addition, the introduction of maneuvers is made manually. Therefore, the trajectory optimization was updated with a path optimization method that makes profit of the rhombic like configuration with a different path for each wheel. The proposed method, described in [1], proposes an initialization of the path planing based on rough paths provided by global planners like the Rapidly-Exploring Random Tree (RRT), [12], or the Probabilistic Roadmap Method (PRM) [13] and redefines the *elastic bands* concept, [14], to evade the common approach that formulates paths as particle-systems. Inspired on the rigid body dynamics, consecutive poses along the rough path previously referred are treated as rigid bodies that are repealed from obstacles through external forces, improving path clearance. Additionally, interactions provide path connectivity and guarantee smooth transitions between vehicle poses. This formulation allow to explicitly consider the vehicle geometry during the optimization and fully profit from the high maneuverability of rhombic vehicles, as illustrated in Figure 5.

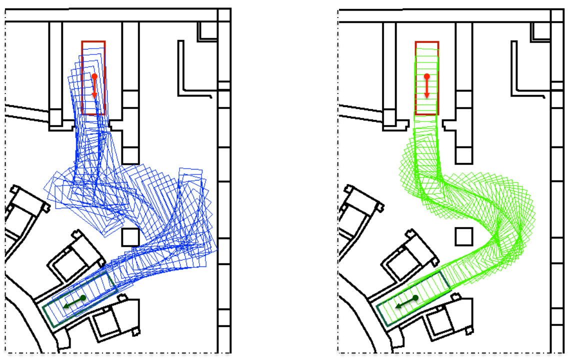

Fig. 5. The collision-free query path is not feasible for execution (left); the final optimized paths for each wheel; which provides a feasible and reliable path ensuring a good clearance over the obstacles (right).

The path optimization proposed in [1] works as a post processing method, which, based on a deformation process, refines and improves the quality of a rough solution path provided by a planner. This rough path, which defines the input for the optimization process, is considered to be a set of collision-free motions connecting the start and the goal vehicle configurations. From this time forth the rough path will be referred to as query path.

In the path optimization process, each of the consecutive vehicle poses that form the query path is treated as a rigid body that is connected with its adjacent poses, like a convoy through internal interactions and subjected to external-repulsive forces produced by obstacles in its vicinity. Hence, the path optimization becomes a path deformation problem, which relies on the principles of rigid body dynamics to iteratively simulate the evolution of each pose on the optimization process. In particular, it is proposed to subject each vehicle pose in the query path to two types of efforts:

- **Internal efforts** - Consecutive poses are kept connected through virtual elastic and torsional springs, which simulate the Hooke's elasticity concept and originate **elastic forces** and **torsional torques**. These efforts guarantee smoothness on deformation and help to shorten the path;
- **External efforts** - **Repulsive forces** repel the rigid poses from obstacles, acting as a collision avoidance feature. Moreover, force eccentricity originates **repulsive** rotating **torques**, which readapt poses orientation maximizing clearance over the obstacles.

The novel method disregards line guidance approaches as the ones proposed in [15] with the resulting optimized path defining an independent reference for each wheel. Loosely following the *elastic bands* concept proposed in [14], this method, by considering each vehicle pose as a rigid body, enables the path deformation to explicitly consider the vehicle geometry and exploits the rhombic vehicle nature, issues that are unattended on similar studies.

D. Simulated results

Using the first approach, as presented in [3], a total of 46 trajectories were computed on TB from which 18 have at least one maneuver (14 with one maneuver and 4 with two maneuvers). The set of all trajectories on all three levels is shown in Figure 6. The total length of all trajectories in TB is 4.6 km. A total of 19 trajectories were computed for the four levels of HCB of which 4 have one maneuver. There are 6 parking trajectories in total. The set of all trajectories, between the lift and each docking (PP) or parking (PA) location, on all four levels, is shown in Figure 7 where each location is identified. In level L1, besides the lift, the CPRHS can also enter in the HCB from an alternative route, the Neutral Beam (NB) (see Figure 7 in c). Using the second approach different paths for each wheel, other trajectories are being evaluated in the same buildings, but with other CPRHS profiles and other types of missions, as in rescue and parking operations. Figure 8 illustrates a rescue operation in one port of TB where a rescue cask has to dock on the rear of a docked CPRHS. The mission cannot be accomplished with the same path for both wheels.

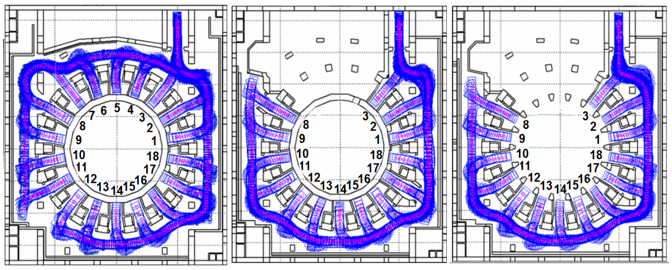

Fig. 6. Set of all trajectories in TB in levels B1, L1 and L2 (same path for both wheels).

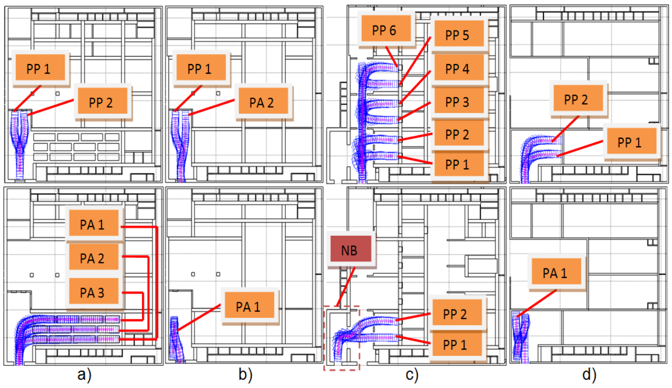

Fig. 7. Set of all trajectories in HCB. In a): level B2; b): level B1; c): level L1; d): level L3. Top: docking locations; Bottom: parking locations (same path for both wheels).

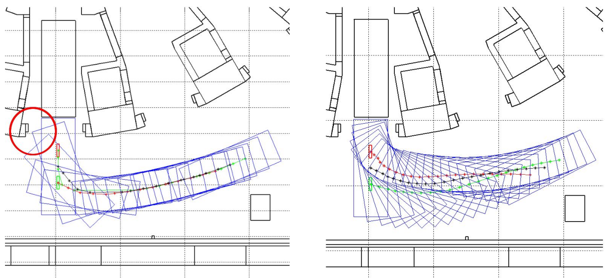

Fig. 8. Trajectories for rescue operation in a port of TB: using a common path for both wheels results in collision (left) and different path for each wheel is well succeeded (right).

III. LOCALIZATION

To navigate along the optimal paths, when line guidance is not used, it is necessary to estimate, in real time, the pose (position and orientation) of the vehicle. Therefore, a localization system is required.

During ITER maintenance operations, the CPRHS transports radioactive products that is the main radiation source when traveling in the environment. Radiation can decrease rapidly the lifetime of onboard sensors, so an option is to install them on the building where the radiation only passes by. The proposed solution for a localization system is based on a network of Laser Range Scanners installed in the scenario and an estimation algorithm for processing acquired data. Using sensors, the poses of multiple vehicles can be estimated simultaneously with the same sensor network, which would be impossible with on board sensors.

A. *Optimizing range finder sensor network*

The sensors network must guarantee a complete coverage of the environment. This requires the optimal placement of each laser achieves with the minimum number of sensor scanners. The coverage function along the state space is non smooth, non-convex and hard to optimize. As the number of sensors increases, the optimization difficulties increase exponentially. The adopted solution is a Monte Carlo optimization approach, using Simulated Annealing (SA) to optimize the number of sensors and its best placement to maximize the coverage area of the scenario, as described in [7]. The Figure 9 illustrates the best configurations of a network of 1, 2 and 3 laser scanners in a scenario of TB.

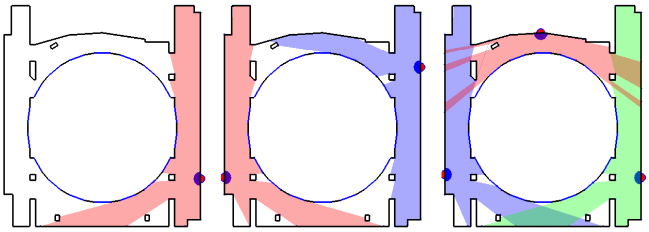

Fig. 9. The best solutions of coverage using 1, 2 and 3 sensors.

B. *Extended Kalman Filter and Particle Filter approaches*

Based on the data acquired by the sensor network, an algorithm estimates the mobile robot position and orientation. Two estimation algorithms were evaluated and compared: Extended Kalman Filter (EKF) and Particle Filter (PF). The PF requires more computation effort, but performs more accurately and more robust to multi-modal observations models and also to failure situations. Based on the results presented in Table I, the PF was found to be a good option for a real implementation.

	EKF		**PF**	
	Position [mm]	Orientation [deg]	Position [mm]	Orientation [deg]
Mean error	546.3	4.5	47.7	0.07
Error std deviation	1122.2	93.4	35.2	0.87

TABLE I

LOCALIZATION METHOD EVALUATION

However, there are still open issues that can be addressed to improve the localization system:

- **Redundancy optimization** - Include the redundancy optimization in the SA.
- **Calibration system** - To compensate for possible errors between the computed sensors placement and the real installation in the scenario.
- **Computation effort** - Reduce the computational power required by the PF algorithm, employing, for instance, only the data acquired by the sensors in the vicinity of the current position of the mobile robot.
- **Multiple vehicles** - The proposed localization system is able to support multiple mobile robot profiles (e.g. with different dimensions) and also operating simultaneously.

IV. NAVIGATION

During maintenance operations when the transportation is required, the optimized paths (real or virtual) are the input for a path following control system that drives the CTS. The path following system controls the CTS engines in real time to keep the wheels as close as possible to the optimized paths and velocity profiles, given the feedback acquired by sensors. According to the path representations, different control systems can be used:

- Line guidance control systems that, based on sensors (usually placed close to the wheels) that detect the deviation of the CTS relative to the path defined at floor level, correct the vehicle position and orientation to take the vehicle on top of the real path.
- Free-roaming control systems that, based on the comparison between the virtual path and the real vehicle location relative to the virtual path (obtained for instance by a GPS localization like system), correct the vehicle position and orientation to take the vehicle on top of the optimal virtual path.

At this actual stage of development, the final choice of the navigation strategy has not yet been made. Regardless of this choice, the control systems should provide the ability to a full autonomous guidance of the CTS/CPRHS. All the operations must be remotely supervised by human operators and, in case of failure, the autonomous guidance might be suspended and a manual mode must be available. As described in [19], three navigation modes were proposed for the operation of the CTS/CPRHS: automatic, semi-automatic and manual. In the automatic mode, the control system drives the CTS/CPRHS along the path according to the velocity profile and the human operator only supervising the mission. In semi-automatic mode, the control system drives the CTS/CPRHS along the path, but the speed is manually defined in real time by the operator. In manual mode, the operator has a full control over the motor wheels of the CTS.

Human being is not allowed in the environment during maintenance operations. Hence, cameras and other sensors must be installed in the scenario to gather a perception of the environment. The data acquired by the cameras and sensors must be integrated and displayed for a better perception insight. In [19], it was proposed a Virtual Reality System (VRS), as illustrated in Figure 10, which includes the model of the scenario, the CPRHS in operation, the simulation of video cameras in different configurations and information about the distance of the vehicle to the closest obstacles.

The VRS is used in all navigation modes for supervising the operations. In particular, in semi-automatic and manual modes the VRS has an interface for the human operator to send commands for driving the vehicle. In semi-automatic mode, it is only required inputs to control the speed of the vehicle, but in manual mode, it is necessary to control the speeds and orientations of the wheels. Therefore, the VRS already integrates Human Machine interface (HMI) devices. A HMI device can be a common keyboard or mouse, a joystick, a gamepads or other haptic devices equipped

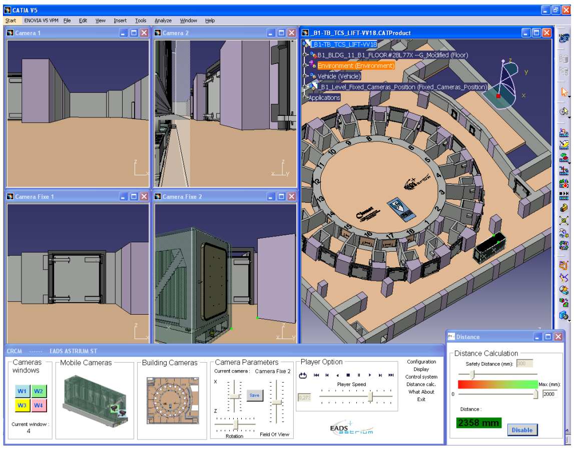

Fig. 10. Virtual Reality system developed by ASTRIUM ST for operation supervision of remote handling operations of transportation under the grant F4E-2008-GRT-016 leadered by IST.

with digital buttons and analog sticks to control speeds and orientations. The paper [2] describes and compares different combinations of manipulating digital buttons and analog sticks to control two independent steerable and drivable wheels of rhombic like vehicle in manual driving mode.

V. CONCLUSIONS

This paper presents an overview of the work developed by IST in the field of remote handling operations in ITER related with transfer casks systems. Actually, a new approach of trajectories optimization is under development, which computes optimized trajectories with different paths for each wheel. This new approach is intended to take advantage of the rhombic structure of the CPRHS in confined spaces, as in parking operations and in rescue missions. The localization problem was also addressed using a approach that optimizes the number and location a network of laser range finder sensors installed on the scenario and Extended Kalman and Particle Filtering methods to estimate the position and orientation of the casks in real time. In the field of navigation, a Virtual Reality System was developed for missions supervision with studies of integration of Human Machine Interfaces devices. The trajectory guidance and path following is still an open issue that will be addressed in the short term.

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