Flexible Path Optimization for the Cask and Plug Remote Handling System in ITER

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Abstract

The Cask and Plug Remote Handling System (CPRHS) provides the means for the remote transfer of in-vessel components and Remote Handling equipment between the Hot Cell Building and the Tokamak Building in ITER along pre-defined optimized trajectories. A first approach for CPRHS path optimization was previously proposed using line guidance as the navigation methodology to be adopted. This approach might not lead to feasible paths in new situations not considered during the previous work, as rescue operations. This paper addresses this problem by presenting a complementary approach for path optimization inspired in rigid body dynamics that takes full advantage of the rhombic like kinematics of the CPRHS. It also presents a methodology that maximizes the common parts of different trajectories in the same level of ITER buildings. The results gathered from 500 optimized trajectories are summarized. Conclusions and open issues are presented and discussed.

Keywords: ITER, Remote Handling, Cask and Plug Remote Handling System, Motion Planning, Free Roaming Navigation

1. 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. The Cask and Plug Remote Handling System (CPRHS) provides the means for the remote transfer of clean/activated/contaminated in-vessel components and remote handling equipment between the Hot Cell Building (HCB) and the vacuum vessel in Tokamak Building (TB) through dedicated galleries, as illustrated in Figure 1.

There are different CPRHS configurations. The largest one has dimensions 8.5m x 2.62m x 3.62m (length, width, height) and is entrusted with the transportation of heavy (total weight up to 100 tons) and highly activated components, [7]. The CPRHS comprises three sub-systems: a cask envelope containing the load, a pallet that supports the cask envelope and the Cask Transfer System (CTS). The CTS acts as a mobile robot, provides the mobility for the CPRHS and can be decoupled from the entire system. Its kinematics configuration, first proposed in [3], 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, become activated. When such components have to be removed for maintenance, operations are to be carried out by the CPRHS, which is required to dock in pre-defined vacuum vessel port cells located on the levels of TB: divertor, equatorial and upper level. Then, the components are transported to the HCB for operations of diagnose and refurbishment or disposal of activated material.

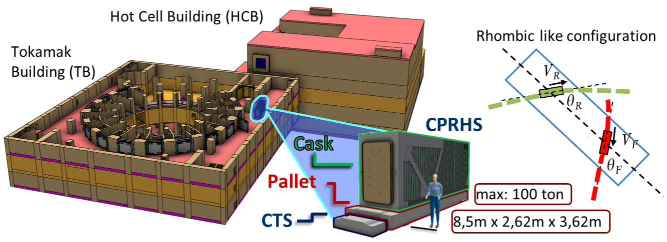

Figure 1: The Tokamak Building, the Hot Cell Building and the rhombic like vehicle for remote handling operations of transportation.

The CPRHS trajectories that support these transportation missions must be optimized in order to maximize the distance to the obstacles and the motion smoothness, while minimizing the path length. A first approach for CPRHS trajectory optimization was previously proposed by the authors in a work carried out under the grant F4E-GRT-016 that specified line guidance as the navigation methodology to be adopted (the approach is described in [8] and the results summarized in [10]).

The application of line guidance methodology leads to non feasible paths in some situations, in particular when moving the CTS from beneath the CPRHS and in rescue operations, when the rescue cask has to dock in the rear and aligned with the CPRHS. To overcome these limitation, this paper presents a complementary approach for path optimization inspired in rigid body dynamics that takes full advantage of the rhombic like kinematics of the CPRHS, yielding different paths followed by each wheel and that provides feasible trajectory solutions that

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were not available in cases when both wheels were constrained to follow the same path under the line guidance navigation methodology. This work was carried out under the grant F4E-GRT-276 that opened the possibility to study free-roaming navigation. As in the first approach, the obtained paths are smooth and maximize the clearance to the closest obstacles. The proposed approach is successfully used in parking operations in HCB, in ports of TB where two CPRHS have to dock simultaneously, for moving the CTS from beneath the pallet inside the ports and in rescue situations.

Given the geometry of the buildings and the similarities of different paths in normal operations, the paper also presents a methodology that maximizes the common parts of different paths in the same level of the buildings. In particular, from the lift to each port in each level of TB, the various paths share the largest possible component around the Tokamak galleries.

The paper organization is the following. The Section 2 explicits the limitations of the line guidance approach developed in a previous work, while Section 3 describes the proposed motion planning methodology based on free roaming navigation. Section 4 describes the additional feature of maximizing common parts of different trajectories. Section 5 presents the results, followed by the conclusions in Section 6.

2. Line guidance limitations

From past studies related to the CTS design, [3], this vehicle has a rhombic kinematic configuration with two pairs (one for spare purposes) of drivable and steerable wheels positioned on the front and rear of the vehicle (see Figure 1). This kinematic configuration endows the transporter with a high maneuverability and flexibility, which are key traits when considering the cluttered nature of the ITER environments. Additionally, in the studies described in [3], the optimized paths would be implemented on the scenario using buried wired systems. The CTS would follow the path by using a line guidance approach with both wheels following the same path, defined at floor level, and therefore the inherent rhombic flexibility (that allows different paths for each wheel) was only partially explored.

Figure 2 illustrates part of the scenario in TB where a rescue vehicle has to dock in a port where another CPRHS is parked. For the particular case where both wheels are constrained to follow the same path (Figure 2-left) no feasible solution is found. Even the inclusion of maneuvers in the line guidance approach, [10], which improved the clearance of some trajectories, can not provide feasible trajectories in most of the critical situations. The achievement of the solution depicted in Figure 2-right, using free roaming navigation, requires the use of dedicated motion planning techniques, in particular, the employment of an efficient path optimization method capable of handling the high maneuvering ability of the rhombic vehicle, in particular having each wheel following a different path.

3. Free roaming improvement

As in the line guidance approach, the evaluation of a free roaming optimized trajectory is divided in three stages: geometric path evaluation (given the environment model and initial and goal objectives, an initial geometric path is found), path optimization (receives the preceding geometric solution as input and returns an optimized path; a clearance based optimization is carried out to guarantee a collision free path that meets the safety requirements) and trajectory evaluation (a velocity function is defined along the optimized path transforming it into a trajectory, which is the output of the proposed planning approach, i.e., a 2D trajectory to be followed by the vehicle).

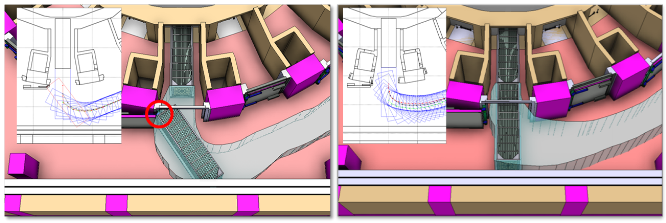

Figure 2: The line guidance approach for the rescue mission in port cell 14 of any level of Tokamak Building results in clash (left image) while the free roaming provides a feasible solution (right image).

To evaluate the geometric path in the free roaming approach a randomized method that acts on rough paths provided by global planners like the the Rapidly-Exploring Random Tree (RRT), [6], or the Probabilistic Roadmap Method (PRM), [2], is used. The RRT algorithm was first presented in [4] as a randomized data structure suitable for a broad class of motion planning problems. The seminal form of the RRT algorithm [4] grows a single tree from the initial configuration, until one of its branches reaches the goal configuration. In each iteration, a feasible configuration (collision free) is randomly generated. An interesting improvement discussed in [5, 6] consists on growing two trees, rooted at the initial and final poses (pose = position and orientation). This variant was implemented in [11] and used in the free roaming approach.

The geometric path returned by the RRT is a collision-free path that accounts for the vehicle geometry. However, a rough and low quality solution is obtained, which presents small clearance over the obstacles and induces jerky motions that do not favor tracking purposes. The use of a path optimization technique is thus required aiming at achieving a feasible solution that can be followed by the rhombic vehicle. Inspired on the rigid body dynamics, consecutive poses along the previously obtained rough path are treated as rigid bodies that are repelled from obstacles through external forces, improving path clearance. Additional interactions provide path connectivity and guarantee smooth transitions between vehicle poses. The Figure 3 illustrates the free roaming process.

The path optimization results from 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. Each vehicle pose is subject to an internal effort (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) and an external effort (repulsive forces repel the rigid poses from obstacles, acting as a collision avoidance feature).

Loosely following the elastic bands concept proposed in [1],

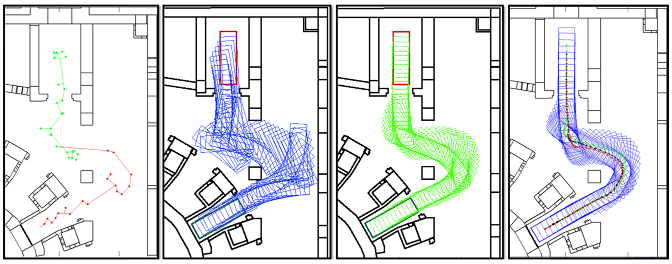

Figure 3: Example of free roaming approach applied to trajectory evaluation to port 2 in equatorial level of TB (from left to right: the initial map with the geometrical path returned by the RRT algorithm, the poses of the vehicle along the initial path, the optimization and the final path.

this method, by considering each vehicle pose as a rigid body, enables the path deformation to explicitly consider the vehicle geometry and exploit the rhombic vehicle nature, issues considered until here as unattended on similar studies. The implemented algorithm is detailed in [11].

The output of this path planning methodology is a collision free path, but still requires a speed profile for execution. Given the cluttered environment where the vehicle moves, an initial approach defines the vehicle speed profile as a function of the distance to the obstacles. The velocity assumes low values when the vehicle is closer to the obstacles. Otherwise, the velocity could be higher, under safety levels.

4. Maximization of common parts of different trajectories

The geometry of the scenarios in TB and HCB is such that paths for different missions of the CPRHS can, in certain situations, share common parts. In particular, this is noticeable in the galleries around the tokamak where all CPRHS have to travel in their motion from the lift to each of the port cells. The maximization of common parts in different paths minimizes the overall volume required for CPRHS operation, this being a key issue in ITER design and safety.

Around the galleries in TB an optimal path to be followed using line guidance navigation was generated (Figure 4 - left). It is to be used, as much as possible, in all missions from/to the lift to/from each port that are accessible from the gallery. Two issues arise at this stage: i) where to deviate from this common part of the path to reach a particular port, and ii) which is the optimal path from this deviation point, i.e., splitting points, to the final goal in the port cell. This second part of a complete path, which is usually the most critical one given the risk of clashes, can be implemented using line guidance or free-roaming.

The overall procedure to evaluate an optimized trajectory that considers the maximization of common paths is illustrated in Figure 4 and can be described as follows:

1. Assume as an input the path starting from the lift and describing a ring around the galleries. This path can be evaluated using the same algorithm of Section 2.
2. Obtain a second optimized path from the lift to a specific port. In case of a non feasible trajectory using the line guidance, the second path is evaluated using free roaming. Note that, along the ring, both paths are quite similar.

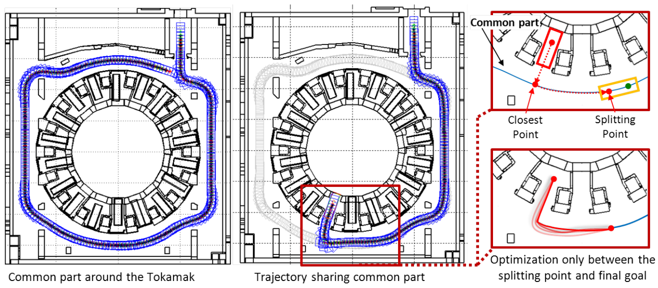

Figure 4: The common trajectory around the tokamak (left image) and the maximization process with the trajectory to port 14 in equatorial level of TB.

3. Starting from the end point of the second path (obtained in point 2) and crawling backwards, the most closest point between the two paths is searched and defined as the Closest Point (CP), as illustrated in Figure 4). From the CP and crawling backwards a constant factor in the first path it is defined the Splitting Point (SP). The common path is defined between the initial point of both paths and the SP.
4. The path starting in the SP, where the pose of vehicle is frozen, and finishing in the target goal is optimized following the same procedure of line guidance described in Section 2 or, if it is not possible, using the free roaming described in Section 3 . This means that the path in point 2 is now disregarded. At this point it is guaranteed the continuity in the splitting point.

The resulted path is finally inputted to the speed evaluator, becoming an optimized trajectory.

5. Simulated results

The algorithms described in this paper were implemented in the software tool Trajectory Evaluator and Simulator, developed by the authors under the grants F4E-2008-GRT-016 and F4E-GRT-276-01. A total of 536 trajectories were optimized in ITER buildings for different cask typologies and satisfying the required safety margin to the closest obstacles. Wherever possible, the line guidance approach is selected to find an optimized trajectory. Figure 5 illustrates the example of port 14 where line guidance can not provide a feasible trajectory, even if including maneuvers. The solution is to adopt the free roaming approach. Given the maximization of common parts of different trajectories, the free roaming is only noticed on the image of the Figure 5 in the vicinity of the entrance to the port, while the other part of the trajectory is accomplished using line guidance.

The line guidance is always adopted as the first choice for the trajectory optimization. However, all the feasible trajectories evaluated using the line guidance approach can also be evaluated or improved using the free roaming approach. In terms of ITER requirements, if a trajectory evaluated using line guidance is feasible for a particular mission, the free roaming is not studied. Even though and for the purpose of this paper, it is shown in Figure 6 the comparison between the two approaches for port 1 in equatorial level of TB, where both approaches are feasible. The differences between the paths are more emphasized in the vicinity of the entrances to the lift and to the port.

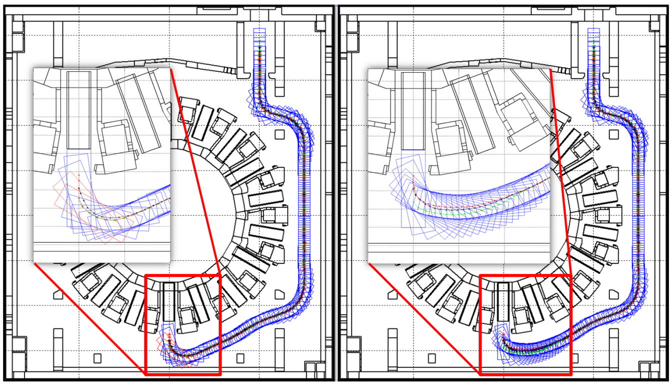

Figure 5: Comparison of non feasible trajectory using line guidance (left image) and the a feasible trajectory using free roaming (right image) to port 14 in equatorial level of TB.

Figure 6: Trajectory to port 1 in equatorial level of TB (from left to right: line guidance and the respective spanned area, free roaming and the respective spanned area.

In addition, the space swept by the cask when moving along a trajectory evaluated by the free roaming approach is larger when compared with the line guidance approach. In the example in Figure 6, the total swept area using line guidance is 173.3 m^2, while using the free roaming is 182.2 m^2. However, as illustrated in Figure 7, the free roaming provides a better safety distance when the vehicle is in the vicinity of obstacles. In particular around the point 40, while entering to the port, the trajectory evaluated by the line guidance approach is closer to the safety margin, while the free roaming approach results in a trajectory with additional 15 cm of safety margin.

6. Conclusions and Future Work

This paper presented a free roaming approach for the trajectory optimization of the CPRHS used in transportation operations in ITER. The free roaming explores the inherent rhombic flexibility and is applied in situations, as rescue operations, where line guidance could not provide feasible trajectories. It was also presented an additional feature that maximizes the common parts of different trajectories in the same level of the buildings. Feasible trajectories were computed for all missions in ITER buildings. In general the free roaming swaps more spanned area, but provides larger clearance in all trajectories and feasible solutions in tight constrained spaces. The maximization of common parts reduces the volume occupied by all trajectories in the same level of each building. The mains results of these approaches applied to the models of the real scenarios have been essential to proceed with the construction of the ITER building given its high priority with respect to the cask trajectories.

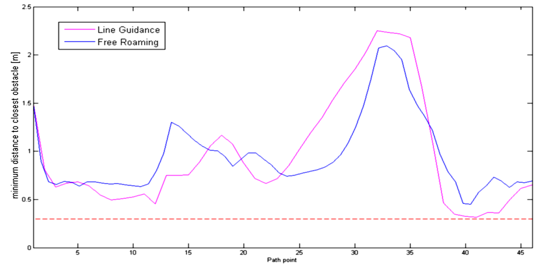

Figure 7: Comparison of minimum distance to the closest obstacles between line guidance and free roaming trajectories to port 1 in equatorial level of TB.

Future improvements will focus on path following strategies for line guidance and free roaming and the integration of localization techniques as the one presented in [9].

Acknowledgments

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