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Human machine interface to manually drive rhombic like vehicles such as transport casks in ITER ⋆

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Abstract: In nuclear facilities, such as the experimental fusion reactor ITER, the cargo transfer operations can be performed by autonomous guided vehicles under remote supervision. In ITER, these vehicles can reach up to 100 tons and, with a rhombic-like configuration, have to move in cluttered scenarios. In case of failure, the vehicles have to be manually guided. This paper presents three solutions for the teleoperation of rhombic-like vehicles. Two set of devices were used to test each solution: one is based on a gamepad and the other is based on a joystick with a rotational disc specially designed for this purpose. The solutions were experimented by the developer and by 12 users without prior experience on rhombic-like vehicles. The experiments were performed in a software simulator that provides 2D maps of the test facility and simulates the kinematics of the vehicles in real time. The main conclusions are reported.

Keywords: Human Machine Interface, Autonomous Guided Vehicles, Manual Driving, Instantaneous Center of Rotation, ITER.

1. INTRODUCTION

A promising plentiful source of energy is nuclear fusion, which is a sustainable and safe method to produce energy. The ITER aims at demonstrating the scientific and technical feasibility of nuclear fusion. Its test facility is under construction in Cadarache, south of France and the first plasma is expected to 2020. The maintenance operations will be remotely performed by robotic manipulators and autonomous vehicles [1]. In particular, the cargo transfer operations will be remotely done by an autonomous vehicle called Cask Transfer System (CTS).

The CTS is a large vehicle with a rhombic-like configuration: two drivable and steerable wheels across is longitudinal axis, which provides omni-directional motion capabilities, its model can be seen in Figure 2. In nominal operations the CTS moves autonomously. However, in certain circumstances such as in failure modes, the vehicle must be remotely driven by an operator.

This paper presents three driving solutions for rhombic-like vehicles: two focused on the wheels and one focused on the center of the vehicle. Typically, large transporters are driven using an hand held device, with the operator staying nearby. When the vehicle is driven focusing on the wheels, the controlling device has a joystick for each set of wheels. Other vehicles are driven focusing on its center,

Fig. 1. Proposed design of a desk for driving operations.

using a device with a 3-axis joystick to control the vehicle position (first two axis) and heading (third axis).

In ITER, human being is not allowed inside the galleries during the transfer operations and, hence, the operator cannot stay in the vicinity of the vehicle. The Figure 1 depicts a desk concept designed to help the driving of the vehicle using the solutions proposed in this paper.

The solution focused on each wheel uses the two joysticks of a common gamepad, each one driving the respective wheel. The solution focused on the vehicle center has two parts: a joystick to manage the velocity vector placed at the center of the vehicle (to control the vehicle position),

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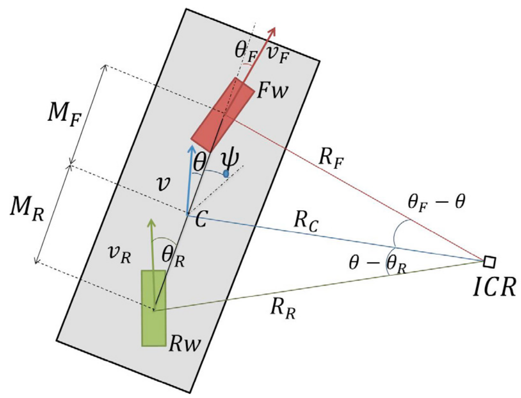

Fig. 2. Model of the rhombic-like vehicle.

and a rotational disc to change the angular velocity (to control the vehicle heading).

The solutions have to be evaluated and, hence, two types of tests were performed: by an experienced user, and by twelve users without experience with rhombic-like vehicles. The selected scenario is the bottom level of the ITER's tokamak building (TB). The goal is to drive the vehicle from a start to an end point, while avoiding collisions and keeping a safety distance from the walls. While driving, the user has visual information of the vehicle position and orientation inside the scenario. During several trials, a set of metrics are used to evaluate the performance of each solution/user and to conclude what is the best solution for driving the CTS.

The paper is organized as follows. Section 2 tackles the necessity to have a solution to manually drive rhombic vehicles and describes the vehicle kinematic model. In Section 3 three solutions for driving the rhombic-like vehicles are preseted and the differences between them are explained. The devices used for the implementation of the solutions are also presented. The Section 4 summarizes the results of testing the solution with an experienced user and with two groups of unexperienced users. Finally, the conclusions are reported in Section 5.

2. PROBLEM STATEMENT

The greatest challenge of manually driving rhombic-like vehicles is given by the number of degrees of freedom. The operator has to drive two wheels at the same time, while taking into account the vehicle heading, dimensions and the scenario along which the vehicle moves. The Figure 2 presents the model of the vehicle.

For driving the vehicle with focus on each wheel, the operator needs to manage four variables: the velocities and orientations of front and rear wheels. The most common problem, while driving the vehicle using this approach, is to mix the front and rear wheels. This means that the vehicle moves on the opposite direction of what the operator expected to do. In addition, the operator pays more attention to the wheels and neglects the safety distances between the vehicle and the closest obstacles.

The ITER facility is a cluttered scenario, providing a narrow margin between the vehicle and the closest obstacles, which increases the difficulty of driving.

The kinematic model of rhombic-like vehicles has two steerable and drivable wheels across its longitudinal axis, which provides omni-directional capabilities (Figure 2).

The variables that will be controlled are the linear velocity vector, which will be split in its two components, the absolute value v and orientation θ, and the vehicle heading ψ which will be controlled via the angular velocity $\dot{\psi}$.

Using the Instantaneous Center of Rotation (ICR) and considering no slippage on the wheels, the line segments R_F, R_R and R_C are orthogonal to their respective velocities, $v_F, v_R and v_C$, with the orientations θ_F, θ_R and θ respectively. Given the distance between the wheels and the center of the vehicle, i.e., M_F and M_R, three triangles are defined: $< ICR, R_w, C >$, $< ICR, F_w, C >$ and $< ICR, R_w, F_w >$. Assuming no slippage on the wheels and the vehicle as a rigid body, the resulted equation is:

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

The angular velocity is the same for all the points of the vehicle body, as explained in [2], and is given by:

$$\dot{\psi}_F = \dot{\psi}_R = \dot{\psi}. \tag{2}$$

From (1) and (2), a duality is found in the linear and angular velocity equations which can be found in (3) and (4). To evaluate the θ only the wheel orientations and positions are required, resulting in (5). The next section presents three solutions to manage these variables.

$$v = \frac{v_F.\cos\theta_F}{\cos\theta} = \frac{v_R.\cos\theta_R}{\cos\theta} \tag{3}$$

$$\dot{\psi} = \frac{v_R}{\cos\theta_F}\frac{\sin(\theta_F - \theta_R)}{M_R + M_F} = \frac{v_F}{\cos\theta_R}\frac{\sin(\theta_F - \theta_R)}{M_R + M_F} \tag{4}$$

$$\theta = \arctan(\frac{M_R.\tan\theta_F + M_F.\tan\theta_R}{M_F + M_R}) \tag{5}$$

3. PROPOSED SOLUTIONS

A previous work was done for driving the vehicle at each wheel, [3]. Using a gamepad, where the joysticks are used to control the orientations of the wheels, while the buttons are used to control the velocities.

The system does not allow the wheels to have configurations that cause slippage or stress on the motors. The wheel orientations are limited and the operator needs to be aware of this while driving with it. This solution is identified in this paper as Gamepad v.1.

Based on the results of [3], the Gamepad v.1 is not a good option to drive the vehicle. In order to make a more efficient and user friendly device, modifications are required. In this paper, the proposed solution using gamepad is implemented as follows: the orientations and velocities of the wheels are totally managed by the two joysticks of the gamepad. The velocity value is always positive and the wheels are free to have any orientation. This solution using gamepad is identified as Gamepad v.2.

In order to develop a device that is safer and easier to drive, a new solution is proposed to drive the vehicle focusing at its center instead on the wheels. Hence, the amount of variables that the operator needs to manage decreases. In relation to the vehicle center, the operator has to control the vehicle's heading, ψ, and the velocity vector, i.e., the absolute value v and orientation θ. The new

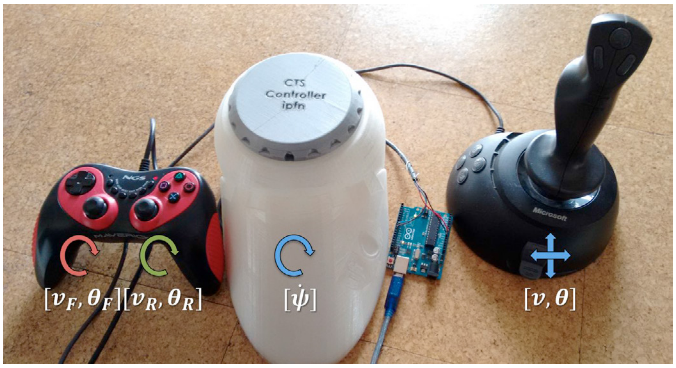

Fig. 3. Gamepad, rotational disk and joystick.

solution is implemented using an off-the-shelf joystick and a new device based on a rotational disk, specially designed for this purpose. The solution is identified as Joystick and Rotational Disk (JRD).

A method to transform the vehicle center variables (v, θ, $\dot{\psi}$) into wheel variables (v_F, v_R, θ_F, θ_R) is required. Three methods were tested, i) split the motion in pure translation and pure rotation movements, ii) the pseudo-inverse of the kinematic model and iii) the forward rate kinematics developed by Alonzo Kelly, that can be seen in [5] and well studied for the autonomous control of a rhombic-like vehicle in [6]. Alonzo Kelly method achieved better results and it is adopted in JRD.

The Gamepad v.1 and v.2 are implemented using a commercial off-the-shelf gamepad, where each joystick controls a different wheel. In Gamepad v.1, the joysticks controls the orientation of the wheels and four buttons controls the velocities. In Gamepad v.2, the joysticks control the v_F, v_R, θ_F and θ_R, where the operator is able to drive the vehicle like a car, locking the rear wheel (or the front wheel in the opposite direction). The gamepad is a NGS Maverick (left side of Figure 3). The devices were implemented and tested on a simulator (TES) [4].

The JRD, depicted in Figure 3, uses a joystick (Microsoft Sidewinder 2-axis), to control the linear velocity vector, v and θ, and the rotational disk to control the angular velocity $\dot{\psi}$. The rotational disk has a Lika I65P encoder connected to an Arduino for data acquisition. In order to have an ergonomically device, a structure was specially designed for this purpose and built on a 3D printer.

4. RESULTS

To evaluate the performance of each solution, several tests were performed with two types of users assuming the role of operator: an experienced user, which is the author of this paper, and twelve users without any experience with rhombic-like vehicles. The three solutions were tested on three different scenarios. In the first scenario the user has to follow a path. In the second scenario the user has to reach three checkpoints in order to complete the mission. Finally, in the third scenario, the user has to drive the vehicle inside the level B1 of TB, from the lift to a port.

The used metrics to evaluate the performance of the solutions were: amount of clashes, safety distance (distance between the vehicle and the closest wall), energy, elapsed time, length of the resulted path, distance between the optimized path and the resulted path, velocity and orientation of the wheels and vehicle's heading. The results are presented in the following figures: the curve in the center is the average value and the gray shaded area represents the standard deviation, in some cases the minimum safety distance is represented by a red horizontal line.

4.1 Experienced user

The scenario 1 is used to evaluate the path following performance, where each solution was tested in 10 trials. The Figure 4 - left presents the map of the scenario and the resulted paths. The Figure 4 - right presents the average and standard deviation of the distance between the optimized path and the resulted path. The Gamepad v.1 is the worst solution given the oscillations in the generated path and the higher values of the distance to the optimized path. The other two solutions have similar results, where JRD presents a slightly better performance.

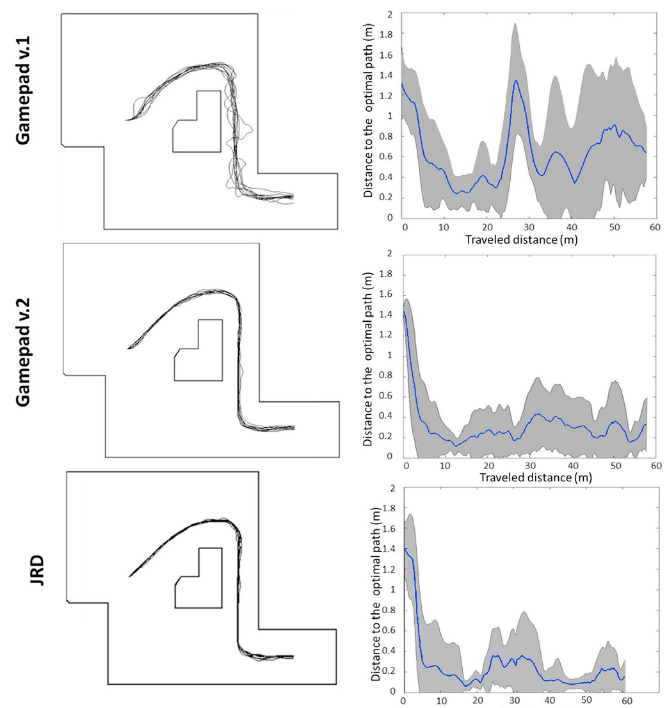

Fig. 4. Resulted paths and distances to the optimal path on scenario 1.

The scenario 2 is used to evaluate the number of collisions and the minimum distance between the vehicle and the nearest wall. Each solution was tested in 5 trials using the map represented in the Figure 5. Collisions only occur when using the Gamepad v.1. The Figure 5 presents the resulted paths and the distance to the closest obstacles. Once again, the resulted paths using the Gamepad v.1 present many oscillations and a lower safety distance to the closest obstacles. Gamepad v.2 and JRD have similar results, with JRD producing the smoothest path curves and less oscillation in the safety distance.

The scenario 3 is used for the overall performance, where each solution was tested in 10 trials. The Figure 6 presents

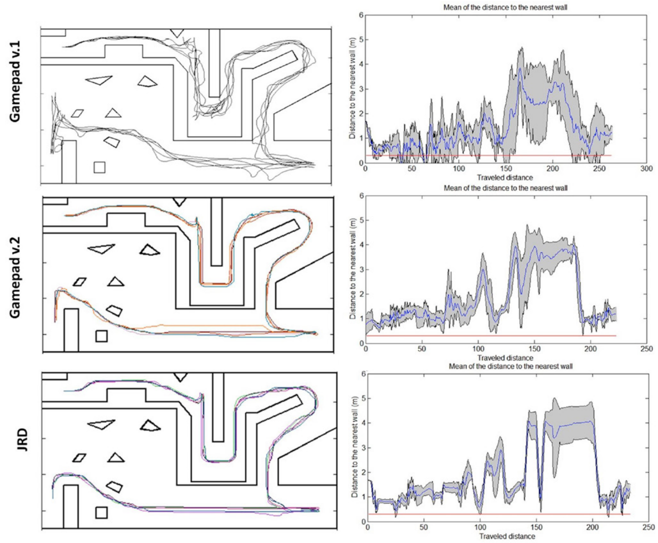

Fig. 5. Resulted paths and distances to the nearest wall on scenario 2.

the used map: part of the level B1 of TB in ITER. Each trial corresponds to drive the vehicle from the lift to the target port. The vehicle is moving in backwards direction given the docking constrain.

The first three images of Figure 6 present the resulted paths of each solution and the last image identifies the zones classified according to the level of difficulty of driving, mainly given the risk of clash. As in the previous two scenarios, Gamepad v.1 produced the worst paths with a high level of oscillations. The other two solutions have similar results producing smooth trajectories. Using the Gamepad v.1 resulted in a total of 30 collisions. No collisions occurred with the other two solutions.

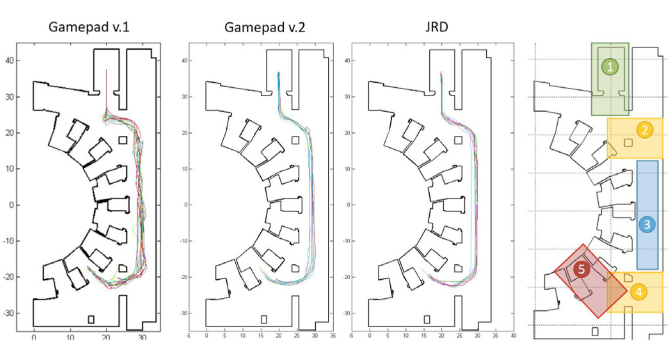

Fig. 6. Resulted paths and the most critical zones of scenario 3.

The Figure 7 presents the vehicle heading and the distance to the closest obstacle. All three solutions have similar heading results. However, Gamepad v.1 detaches from the other solutions given the amount of oscillations in zones 4 and 5. JRD and Gamepad v.2 present results with similar shapes along the entire journey. The three solutions have similar safety distances, where Gamepad v.1 presents the worst performance in zone 5.

In terms of elapsed time to accomplish each trial, using the Gamepad v.1 takes almost two times more than the other two solutions, since the maximum velocity is reduced in order to avoid clashes.

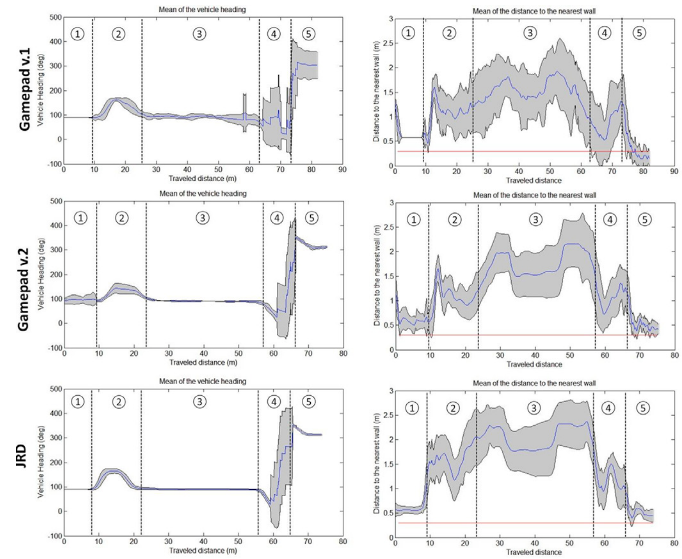

Fig. 7. Vehicle's heading and safety distance.

In summary, the results with the experienced user shown that Gamepad v.1 is not a suitable solution to drive the vehicle and, hence, it was not tested by the users without experience with rhombic-like vehicles. Scenario 3 is the only scenario where the tests will take place because it is easier to evaluate and detect driving profiles.

4.2 User without experience

The users were split in two groups, each one with 6 users. The first group started using the Gamepad v.2 and the second group started using the JRD. After 5 successful trials, the groups exchanged the Gamepad v.2 and JRD between them and completed other 5 trials. All the trials were performed in scenario 3. Before starting with the trials, since the target users had no experience with rhombic-like vehicles, neither experience with the used devices, mainly with the rotational disk, a scenario 0 was created for demonstration. The scenario 0 has the same map of scenario 1 and is used for introduction and tutorial purposes. Each user had the opportunity to test the devices, without any concern related with clashes or other constrains. As soon as the user becomes confident with the device, the trials proceeded to the scenario 3. In scenario 3, a user has to drive the CTS from inside the lift to a docking port in the shortest period of time and without any collision. The vehicle's rear wheel is the first to leave the lift, so it is typically seen as the main wheel.

The users are all between 11 to 50 years old, with an average of 26 years old. All of them have experience with computers and 58% had experience with console games and gamepads. Each user had to complete five trials, i.e., driving from the starting position to the goal without collisions. In case of clash, the trial is interrupted and restarted with the vehicle placed at the initial position. A total of 200 trials were performed, with 120 successful trials and 80 interrupted trials where a clash was detected.

According to the zones identified in Figure 6, the collisions happened almost in the same places using Gamepad v.2 or JRD: near to the pillars in zones 2 and 4, and near the docking part, in zone 5. A high number of collisions are verified along the corridor, because it is harder to follow a straight line using the Gamepad v.2.

The Table 1 shows the total number of collisions. The Gamepad v.2 resulted in a higher number of collisions and most of the collisions happened in Group 1, because they are not enough self confident and had to learn how to navigate in the scenario with Gamepad v.2 first. The same behavior is seen in Group 2 with the high amount of collisions with JRD.

Table 1. Total number of collisions.

	Gamepad v.2						JRD					
# Trial	1	2	3	4	5		1	2	3	4	5	
Group 1	28	8	4	2	1	43	0	1	5	1	0	7
Group 2	13	0	4	3	0	20	3	3	2	0	2	10
Total	41	8	8	5	1	63	3	4	7	1	2	17

The resulted paths in these tests are similar to the experience (Figure 6).

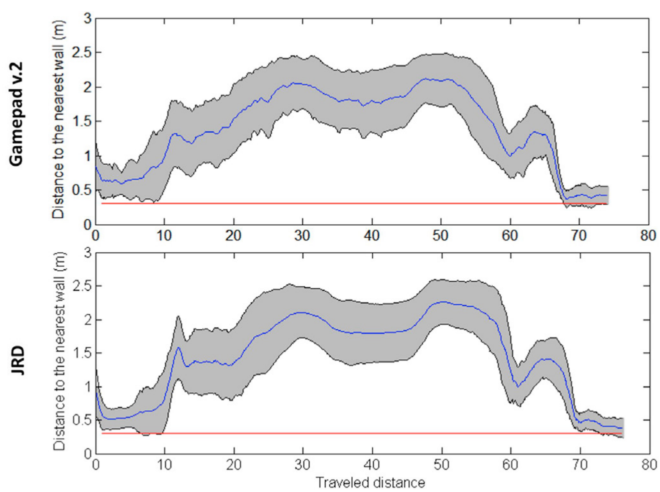

Fig. 8. Distances to the nearest wall.

The Figure 8 shows the average and standard deviation of the distance to the closest obstacle represented by the blue curve and the gray area, respectively. The values and shapes of the curves are similar. The lower values are located at the start and at the end of the trials because those locations have the narrower areas. The curve generated by Gamepad v.2 shows more oscillations than JRD results, this means that the paths produced by Gamepad v.2 have more oscillations than JRD. The Figure 9 presents the vehicle's heading, where both graphs have similar values and shapes.

The Figures 10 and 11 present the wheel orientations if using Gamepad v.2 and JRD, respectively. In JRD, the plots associated to both wheels are quite similar and with a low standard deviation, which means that the users had a similar driving. With Gamepad v.2, the front and the rear wheels present different shapes. The rear wheel results are similar in JRD. However, the standard deviation of the front wheel is very high, because some users drove the vehicle like a car, freezing the orientation of the front wheel and only considering the rear wheel.

The Figures 12 and 13 present the wheel velocities for Gamepad v.2 and JRD, respectively. The velocity of both wheels have the same shape using JRD. With Gamepad

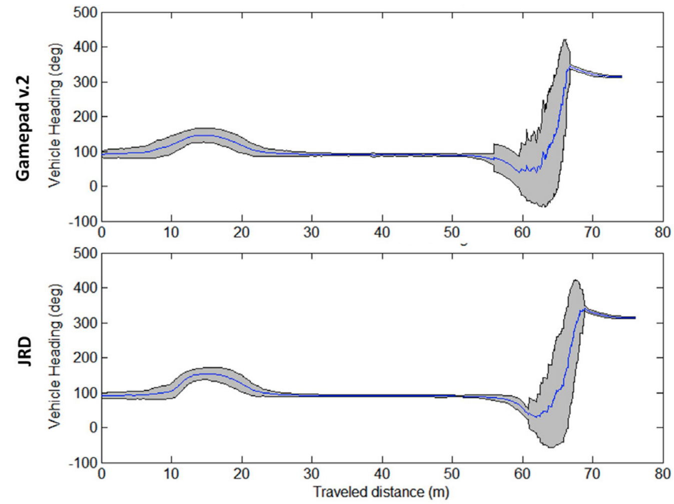

Fig. 9. Vehicle's heading.

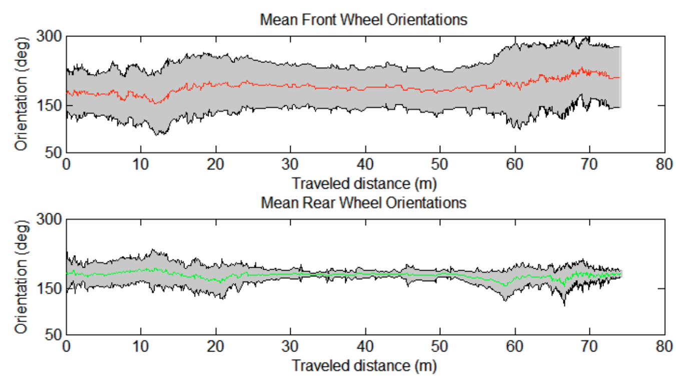

Fig. 10. Orientations of the wheels using Gamepad v.2.

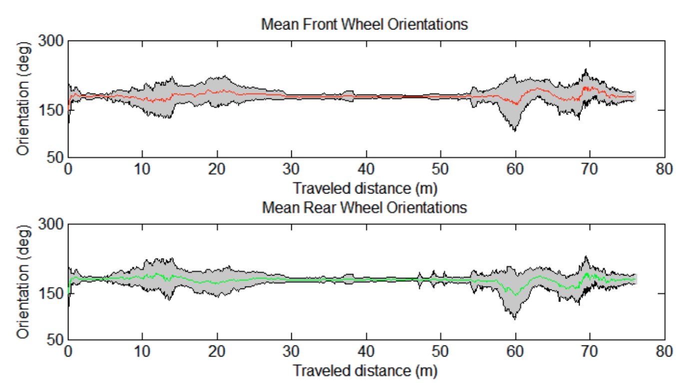

Fig. 11. Orientations of the wheels using JRD.

v.2 the velocity results show the same behavior as the orientations: the front wheel has a large standard deviation because users drive the vehicle as a traditional car.

The Figure 14 presents the duration, length and energy for each wheel. The duration and length values for Gamepad v.2 and JRD are very similar, with JRD values being slightly higher. In terms of energy, both wheels have similar values with JRD. With Gamepad v.2 the energy values of the rear wheel are higher than the front wheel, since the users drive the vehicle like a traditional car.

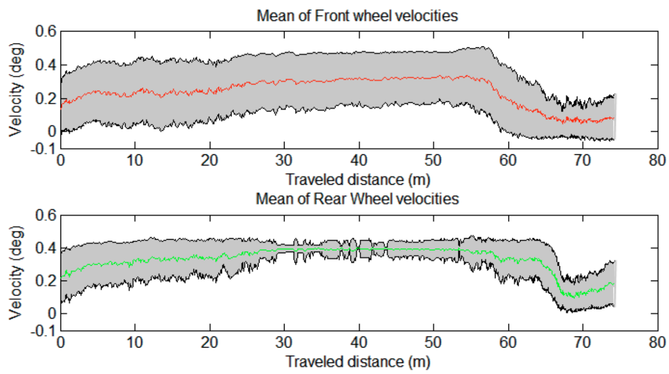

Fig. 12. Velocities of the wheels using Gamepad v.2.

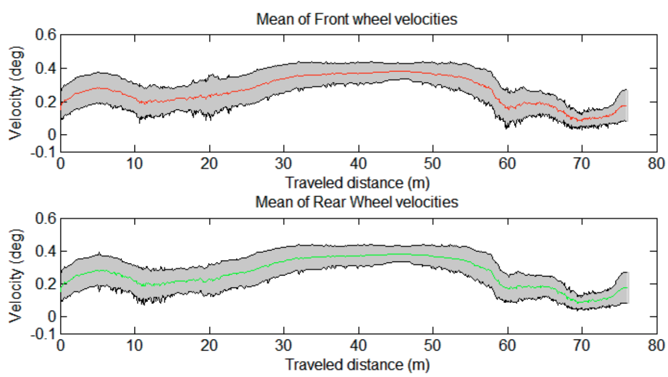

Fig. 13. Velocities of the wheels using JRD.

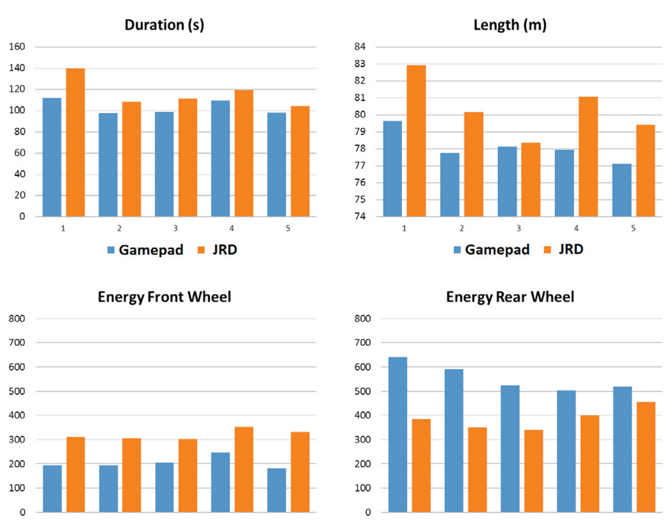

Fig. 14. Duration, length and energies of all trials performed by all users.

All the users agreed that driving the vehicle at its center with JRD was easier and more intuitive than driving each wheel with Gamepad v.2, which is confirmed by the total number of collisions presented in Table 1. However, some users thought that, with time and practice, Gamepad v.2 should be better than JRD given the freedom that it provides. Most users were focused mainly on the rear wheel of the vehicle when driving with Gamepad v.2, driving it as a car. The approach of driving the rhombic-like vehicle as a traditional car was never considered with JRD.

Fig. 15. Rhombic like vehicle built in LEGO to copy the cask in ITER, at the scale of 1:25.

5. CONCLUSIONS

This paper presented and compared three solutions for manual driving of rhombic-like vehicles. Two solutions are based on a gamepad and one based on a joystick with a rotational disk, specially designed for the purpose of this paper. The first solution, already presented in a previous work, was tested and discarded given the bad results, even with an experienced user. The other two solutions, Gamepad v.2 and JRD can accomplish the mission of manual driving in cluttered scenarios. With Gamepad v.2 the vehicle retains all of its motion capabilities, but the user tends to drive the vehicle as a traditional car, producing more mistakes. The JRD provides a easier and more intuitive driving mode, where the vehicle motion are constrained, but keeping its omni-directional capabilities. In summary, the JRD is the best option, keeping the Gamepad v.2 as a second option.

Preliminary tests were performed with a rhombic like vehicle similar to the CTS with a cask, built in LEGO at the scale 1:25, as illustrated in Figure 15. The first conclusions are similar to the ones achieved in simulation. However, new experiments are being performed, as well as the to develop a device that combines both solutions: JRD for a typical trajectory and Gamepad v.2 for complex trajectories that require extra motion freedom.

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