2021 IEEE International Conference on
Autonomous Robot Systems and Competitions (ICARSC)
April 28-29, Santa Maria da Feira, Portugal

2021 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC) | 978-1-6654-3198-9/20/$31.00 ©2021 IEEE | DOI: 10.1109/ICARSC52212.2021.9429776

Simulation of a Robotic Co-transport System

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***Abstract*—The transportation of large loads is still an obstacle to the productivity of some companies. To answer this internal logistics challenge, one solution with high potential is the use of several mobile robots that can execute these tasks cooperatively. This paper addresses the simulation of strategies that allow two omnidirectional robots, a leader and a follower, to coordinate their movement and cooperate in a transportation task (co-transport). This is achieved by implementing a force sensor on the mechanical structure of a support that allows the follower to grab and transport the load on the top of its chassis. Through the measurement of the forces, this robot will be able to react to the movement of the leader, whose function will be to guide the system to its final destination. The system and its cooperation strategies were idealized and then tested in the CoppeliaSim simulator. The results obtained through simulation were the target of an analysis that assessed which strategy best complemented the omnidirectional mobility of the system's constituents and, at the same time, ensured that less forces were exerted on the load during transport.**

***Index Terms*—Multi-Robot Systems, Cooperation, Cooperative load transport, Mobile robotics, Simulation, CoppeliaSim.**

I. Introduction

Mobile robots have been used to automate transport operations in the industry since the middle of the 20th century. More and more companies have these systems, some of which are already made up of numerous fleets that work tirelessly in their factories and warehouses. With the evolution of the market, it is expected that many more will be able to acquire and benefit from the use of these technologies.

As the number of robots available in companies increases, it is important to study strategies that allow them to cooperate with each other. Thus, as happens with humans or animals, machines will be able to work together, overcoming the adversities imposed by certain tasks more easily and in a more efficient way.

The cooperation between mobile robots in transport operations has been studied since the first advances in the area of multi-robot systems (late 20th century) [1]. The interest in this matter arises from the need to create efficient systems that can carry out the transport of bulky, heavy or complexly shaped objects, which cannot be carried by just a single robot. However, in such systems, not all the elements necessarily have to participate directly in the transport of the load [2]. They may also be responsible for monitoring the environment in which the team is located, signaling and even removing obstacles so that the task can be successful. Regardless of the function of each element, the use of co-transport systems can bring several advantages, such as [2], [3]:

- increased dexterity;
- more efficiency with respect to energy consumption;
- more robustness and fault tolerance;
- lower acquisition costs;
- more flexible systems that are, for example, easier to modify or to apply in new scenarios or operations for which they were not initially designed.

In order to benefit from the advantages that may arise from the use of these systems, it is of the greatest interest to study possible ways to establish cooperation between mobile robots. The main objective of this work is to explore, through a simulation environment, cooperation strategies based on the use of force sensors on a system with two omnidirectional robots.

The remainder of the paper is structured as follows. Section II presents previous explored systems. Then, in Section III, the idealized co-transport system that is studied in this project is explained. In Section IV the implemented co-transport strategies are addressed. The results obtained through simulation are presented in Section V. Finally, in Section VI, the main conclusions and some ideas for future work are presented.

II. Related Work

Being such a comprehensive subject that involves many concepts, there is already a considerable amount of studies carried out in the co-transport area. A quite ample literature review was presented by Tuci *et al.* [2], in which the authors classify the studies based on the transport strategy that is employed in each one. Below, are presented brief details of some studies on co-transport systems already conducted, and that are of relevance to this work.

In the project realized by Pereira *et al.* [4] the object of study is the cooperation between two nonholonomic robots (leader and follower) in a transportation task, with the use of implicit communication. To overcome the fact that the robots cannot communicate directly, each one of them has two devices made up with a angular potentiometer and a spring.

This work is financed by National Funds through the Portuguese funding agency, FCT - Fundação para a Ciência e a Tecnologia, within project UIDB/50014/2020.

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This allows to translate the force imposed by the leader on the load, and consequently on the follower, in a variable resistance value. Another highlight of this project is that the robots can change their roles, in order to overcome truck-trailer backing problems, due to the nonholonomic constraints of the system.

In [5], Wang and Schwager present a decentralized algorithm that coordinates a group of four differential drive robots during a transportation task. One of these robots (the leader) is responsible to guide the system to the destination, while the others (the followers) must help applying force to the object being transported. Each follower robot has a gripper with a laser sensor that is used to estimate the velocity and direction of the movement of the object. This gripper is connected to the body of the robot through two load cells mounted perpendicularly. This way, it is possible for the followers to map the bidimensional forces imposed on the object.

Machado *et al.* [6] implemented a leader-helper architecture for a team of two differential drive robots. In their work, the leader drives the system to target locations detected with an omnidirectional vision system. On the other hand, the helper needs to maintain a certain distance to the leader. This is achieved with a two DOF support. During the transport operation the leader moves and the load is displaced along the prismatic and rotational joints of the support. By monitoring the displacement of the joints and knowing the heading direction of the leader (value that is explicitly communicated) the helper can estimate the movement of the leader.

In the GEOMOVE project [7], the authors take inspiration on the tidal locking of two astronomical bodies to implement their co-transport solution. In this system, developed specifically for the aeronautic industry, the two omnidirectional robots do not have any mechanism that allows to grab the load. Instead, the load is simply placed on the top of their chassis. The two robots must then move in a coordinated way so that the load does not fall or suffers torsion forces that may lead to damage. To achieve cooperation, the master robot calculates the velocities of the system, whereas the slave uses its front LiDAR to detect the master's rear profile and correct its alignment.

In the work presented on this paper, such as in [4] and [5], force sensors are used to achieve cooperation. However, the robots are holonomic (as in [7]), which means that they can move instantaneously in any direction from any configuration [8], thus giving the system a greater maneuverability and eliminating some problems related to kinematic constraints. Also, the robots will transport the load on the top of their chassis, something that does not happen in the strategy explored in [5] (the load is dragged across the floor) and that could result in potential damage. When compared to the strategy explored in the project GEOMOVE, using force-sensing methods may also result on more forces applied to the load, however it will also allow to eliminate or reduce drastically the direct communication between the robots. Additionally, in certain applications, the forces imposed on the load, if reduced, may not necessarily be a problem.

III. Idealized Co-transport System

The co-transport system that is simulated in this work consists of two Discovery Q2 omnidirectional platforms [9], a leader and a follower. It has a decentralized architecture, which means that both robots are equally responsible for the control of the transport task, although they have different functions. The leader will plan the trajectory and set the system speed, on the other hand, the follower will measure the forces that result from the movement of the leader, and react in order to counteract them. In respect to direct communication between robots, as already mentioned, it should be nonexistent or, if there is no possible alternative, reduced as much as possible. Since all the explored strategies involve grasping the load, the robots are also constituted by a support that allows the load to be placed on the top of their chassis.

The studied strategies differ depending on the sensors implemented on the mechanical structure of the support and control architecture of the follower. Fig. 1 shows the two types of supports that are simulated in this work. One of them has a multiaxial force/torque sensor that allows the robot to measure, at least, three force components, as depicted in Fig. 1 to the left. On the other hand, the other support has a load cell that only allows to measure forces along one axis. For this reason a revolute joint with an angular position sensor is also included, so that the follower may also know the direction in which the load is being pushed by the leader.

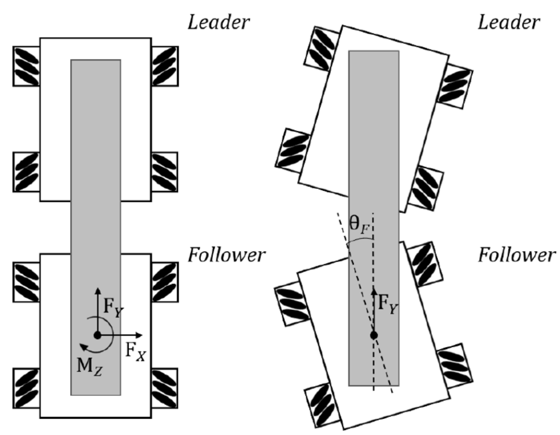

Fig. 1. Different supports used in the simulated strategies

A. Model Creation in CoppeliaSim

The idealized system was modeled in CoppeliaSim [10], the simulator used in this work. Fig. 2 represents the Discovery's virtual model and its hierarchical structure.

The robot's model can be divided in three parts: chassis, mecanum wheels and support. The first one consists only on two cuboid shapes. The mecanum wheels were implemented using a method advised by the simulator's developers and that can be seen in other omnidirectional robot models, found on the CoppeliaSim's model library. Lastly, the support was modeled so that the different strategies could be simulated. Since the robots needed to grasp the object, the behaviour

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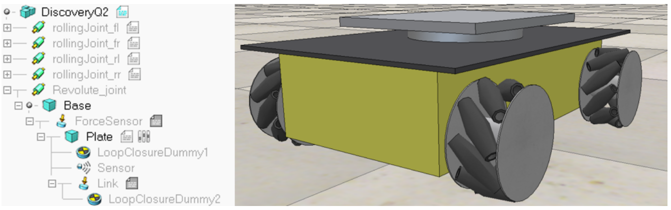

Fig. 2. Discovery Q2 model developed in the CoppeliaSim Simulator

of a suction pad was reproduced on the support's plate. The plate was then connected to a second part of the structure with a force sensor (this scene object is the equivalent of a six axis force/torque sensor, allowing to simulate both sensors needed in this work). Finally, the support was attached to the omnidirectional platform through a revolute joint. This joint can also be locked if the degree of freedom is not needed.

B. Discovery Q2 Kinematic Model

The Discovery Q2 is an omnidirectional robot with four mecanum wheels. A schematic of this type of platform is illustrated in Fig. 3.

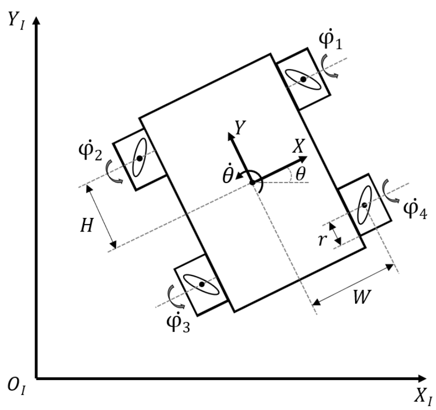

Fig. 3. Schematic of a four mecanum wheels omnidirectional platform (represented rollers are in contact with the ground)

Through the combination of the kinematic constraints of each of the mecanum wheels, it is possible to obtain the kinematic model of the platform [11]. Considering the previously presented schematic and that the angles of the rollers are -45° and 45° (right-handed and left-handed wheels, respectively), the inverse kinematics of this platform is represented by (1), where $\mathbf{J}$ is the jacobian matrix of the system.

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\\ \dot{\varphi}_4\end{bmatrix} = \mathbf{J}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} = -\frac{1}{r}\begin{bmatrix}-1 & 1 & W+H\\ 1 & 1 & -(W+H)\\ -1 & 1 & -(W+H)\\ 1 & 1 & W+H\end{bmatrix}\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\theta}\end{bmatrix} \tag{1}$$

To calculate the velocities taking into account a global coordinate system, the rotation matrix $\mathbf{R}(\theta)$ can be used, according to (2).

$$\begin{bmatrix}\dot{\varphi}_1\\ \dot{\varphi}_2\\ \dot{\varphi}_3\\ \dot{\varphi}_4\end{bmatrix} = \mathbf{J}\mathbf{R}(\theta)\begin{bmatrix}\dot{x}_I\\ \dot{y}_I\\ \dot{\theta}\end{bmatrix} \tag{2}$$

$$\mathbf{R}(\theta) = \begin{bmatrix}\cos(\theta) & \sin(\theta) & 0\\ -\sin(\theta) & \cos(\theta) & 0\\ 0 & 0 & 1\end{bmatrix} \tag{3}$$

IV. Implementation of the Co-transport Strategies

This section addresses the control architecture of the constituents of the co-transport system. It should be emphasized that, since the objective of the leader is to guide the system to its destination, its control architecture will be the same regardless of the strategy. The changes occur only on the side of the follower, depending on the support structure and control architecture implemented, as already mentioned. The models' control in the simulator was achieved using Lua scripts.

A. Leader's Control Architecture

Besides manual control with the keyboard (made possible by the simulator function *sim.getSimulatorMessage()*), path following was also implemented so that it was possible to replicate the same experience and compare the studied strategies. Fig. 4 shows how the robot is controlled in this operating mode. The blue parts of the diagram were not addressed in this work and were performed by simulator's properties and functions. Path following was achieved with a PI controller that eliminates the error between a reference position and the actual position of the robot.

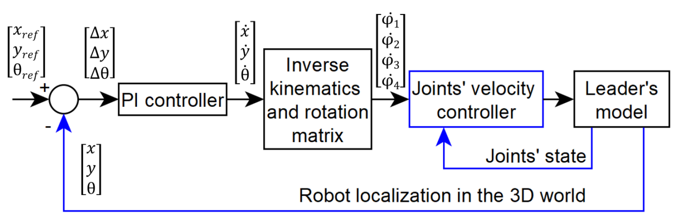

Fig. 4. Block diagram of the path following control

Paths can be easily generated in CoppeliaSim by creating and editing path objects. Additionally, they can also be imported in CSV format. Using the editing mode, the user can define various properties of the path, such as introducing control points and define their position and orientation in the virtual world, perform linear interpolation between control points through Bézier curves, and so on.

B. Follower's Control Architecture

1) Strategy 1: In this strategy it is assumed that the support mounted on the follower's chassis has a multiaxial force/torque sensor (Fig. 1, to the left). By using this sensor, the robot can measure any bidimensional forces/torques that result from the movement of the leader, and estimate the velocity of each wheel in order to counteract them. This is achieved by implementing the control of all the measured force/torque components with a PI controller, as shown in Fig. 5.

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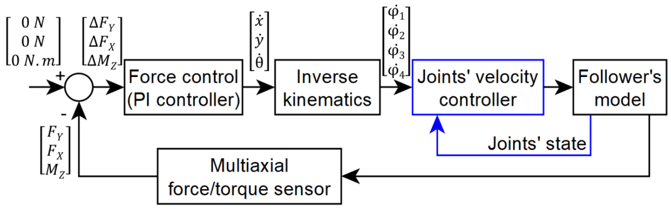

Fig. 5. Block diagram of the control architecture used in strategy 1

2) Strategy 2: In the second strategy the support has a load cell and one revolute joint monitored by an angular position sensor (Fig. 1, to the right). Fig. 6 presents the diagram of the control architecture thought for the follower robot. In order to establish cooperation between the two robots a single PI controller is needed for force control. Knowing the angular position of the support it is possible to calculate the velocity components (as in (4) and (5)) that allow to minimize the components of the force imposed by the leader on the load (F_Y and F_X, as illustrated in Fig. 7). This is possible because the robot does not have nonholonomic constraints. The rotation controller, although not necessary to achieve cooperation, was implemented so that the follower could align itself with the load being transported.

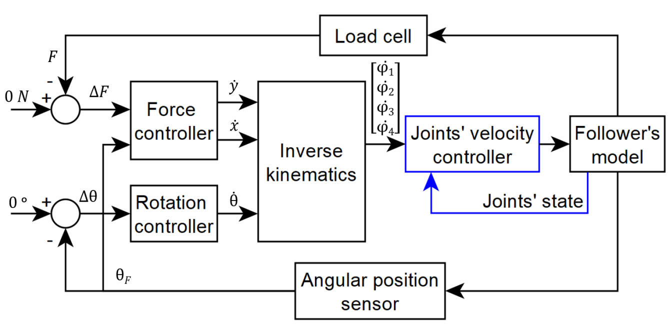

Fig. 6. Block diagram of the control architecture used in strategy 2

$$\dot{y} = -V \cdot sin((\pi/2) - \theta_F) \quad (4)$$

$$\dot{x} = V \cdot cos((\pi/2) - \theta_F) \quad (5)$$

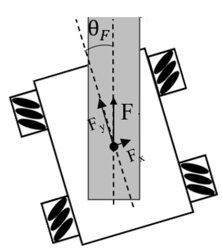

Fig. 7. F_Y and F_X components of the force measured by the load cell

3) Strategy 3: This strategy assumes that the same support as the previous one is used. Additionally, there is also the explicit communication of one parameter. As it can be concluded by analyzing the diagram in Fig 8, the leader needs to communicate its orientation to the follower. Although the ideal was to not use explicit communication, this was the only solution found to combine the best characteristics of the other strategies (as it will be demonstrated in the next section), without using more sensors. When compared with the second strategy, the function of the rotation controller changes and a translation controller is introduced.

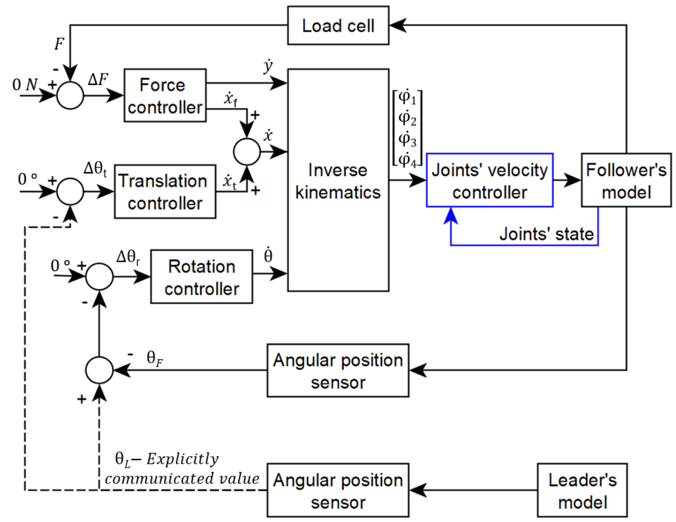

Fig. 8. Block diagram of the control architecture used in strategy 3

The action of the rotation and translation controllers is depicted in Fig. 9. The rotation controller's function in this strategy is to make the follower have the same orientation as the leader, while the translation controller, in its turn, ensures that the two robots are aligned by taking action on the lateral movement of the follower.

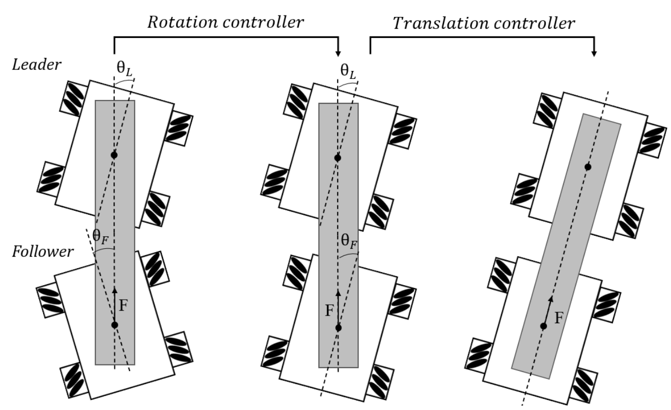

Fig. 9. Function of the rotation and translation controllers

The PI controllers implemented for each of the presented strategies were tuned either manually or by using Ziegler-Nichols second method.

V. Simulation and Results

In order to simulate the co-transport system, a scene was created in CoppeliaSim with the two robots and a cuboid object that represents the load (Fig. 10). Also, an S-shaped path, generated in the simulator, was used to compare the performance of the system using the various strategies. The graphs presented in Fig. 11 and Fig. 12 show how the robots move along the path and the forces that are measured by the force sensor on the follower's support, during a transportation task in which the average velocity of the leader is 0,1 m/s. It is important to mention that these results were obtained with the ODE physics engine and a simulation time step of 10 ms. All the simulations were run on a computer with the specifications indicated in Table I.

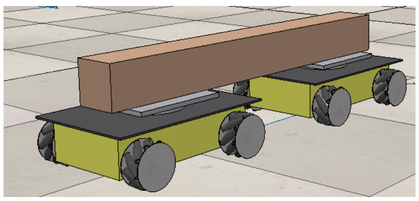

Fig. 10. Co-transport system and load in CoppeliaSim's virtual environment

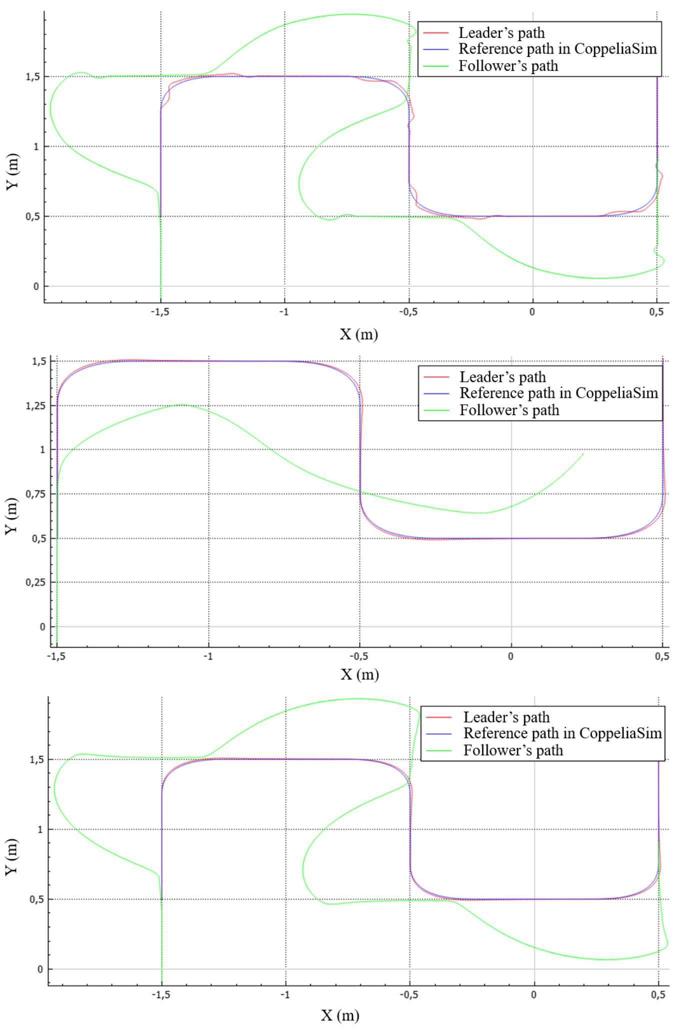

Fig. 11. XY graphs of the robots' position during the movement along the path, for strategies 1, 2 and 3, respectively (top to bottom)

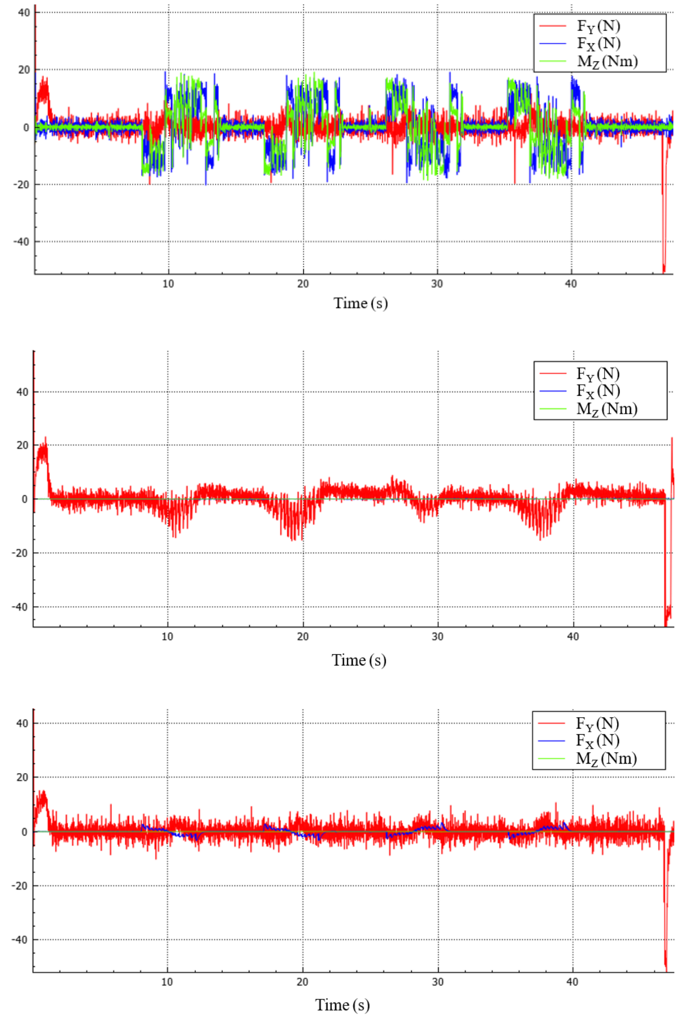

Fig. 12. Forces measured by the follower's support during the transportation task, for strategies 1, 2 and 3, respectively (top to bottom)

TABLE I
SYSTEM'S SPECIFICATIONS

Processor	Intel Core i7-6700HQ 2.60GHz
Graphics Card	NVIDIA GeForce GTX1060 6GB
RAM	16 GB
Operating System	Windows 10 (64-bit)

Through the analysis of the presented graphs, it is possible to draw important conclusions about the studied strategies.

In an initial phase, it was decided to use the multiaxial force/torque sensor (strategy 1). The idea was to verify if it was possible for the two robots to cooperate without the need of explicit communication. Using this sensor would also allow the robots to maintain their relative position and orientation to the load. In other words, the system would be able to keep its formation, something that could facilitate the path planning task. After simulating and obtaining the results, the problems associated with this strategy can be easily identified. Even though the robots are able to cooperate, the load is subjected to much more forces when compared to the other strategies, and the only way to reduce them is if the system moves slower. Another downside is the fact that, since the robots are rigidly connected through the load, the follower has much more influence in the movement of the leader. This is noted mainly in transversal or rotational movements executed by the leader, and originates errors that keep the leader from following the path in a smooth way. Fig. 13 shows an example on how the inertia and the time it takes the follower to react to the forces may disorient the leader, when it starts to move transversely in a more abrupt way.

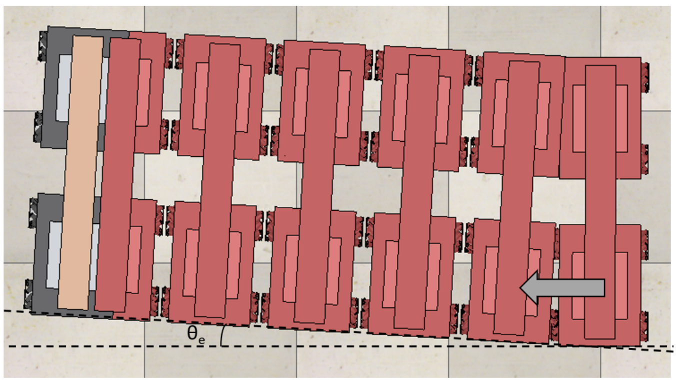

Fig. 13. Exemplification on how the follower's influences the movement of the leader

The introduction of one DOF in the support on the second strategy eliminates the disadvantages appointed to the first one. Shear and torsion forces cease to exist. The robots are able to cooperate in the transportation task and the load is only under tension and compression forces. Additionally, the load cell would also be a more accessible component than the multiaxial force/torque sensor. However, there is one disadvantage. The system breaks formation during transport and loses some of it's omnidirectional capabilities, as it behaves, most of the time, has if it was constituted by differential drive robots.

The third strategy was studied as a way of combining the advantages of the previous ones. The results show that, not only the robots maintain formation with small error, but also are capable of transporting the load with much less forces being imposed on it. The downside is that explicit communication is used, while in the other solutions the robots acted based only on the force measurements. Nevertheless, this was the only way found to combine the best features of the first and second strategies, without considering the use of more hardware.

VI. Conclusions and Future Work

This paper presented the study of a co-transport system utilizing the CoppeliaSim simulator. The main objective was to analyze strategies, based on the use of force sensors, that allowed two omnidirectional robots to cooperate in a transportation task. In this regard, three strategies were idealized, implemented and simulated.

All of the strategies, despite their advantages and disadvantages, allowed the robots to cooperate in the transportation task. An effort was also made in order to find a solution that best complemented the omnidirectional capabilities of the robots and that guaranteed that less forces were imposed on the load. The third explored strategy meets these requirements, however, introduces the need of explicit communication (even if reduced) between the robots. In the future it could be interesting to understand how the follower could align itself with the leader through the use of implicit communication only. An idea would be to explore a similar technique to the one used in the project GEOMOVE using LiDAR technology [7], or even a kinect sensor as shown in [12]. In a real system this would enable to perform tasks in environments where it is not permitted communication or that are prone to errors.

Regarding the control of the system, this work was carried out using PI controllers only. It could be interesting to investigate other types of control and how they would impact the system's performance.

Finally, it would also be interesting to implement the system with the real platforms and see to what extent it would behave like the simulated one.

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