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KINEMATIC AND DYNAMIC ANALYSIS OF A DIFFERENTIAL ROBOTIC PLATFORM WITH CATERPILLAR TRACKS

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ABSTRACT

Caterpillar tracked mobile robots are of wide utility in tasks that require movement in flat, dry environments, with a minor to medium degree of irregularity, and with a relatively high load capacity requirement. Such is the case of robots intended for military applications (e.g., for transporting military equipment), industrial applications (e.g., mobile manipulators), or service applications (e.g., surveillance and care of people). In this sense, it is important to correctly identify the kinematic and dynamic characteristics of such robots to project their possible use in the development of certain tasks, as well as their expected performance. This paper describes the kinematic analysis of the ARMOS TurtleBot 1 robot, a robotic platform developed by the research group for the development of human services tasks. This robot has four caterpillars for its displacement, each of them receives movement from its own DC motor. However, by design, the tracks on each side work synchronously, so the robot has a non-holonomic differential drive. The analysis of the platform consists of the development of two models derived from kinematic analysis and dynamic analysis. In the first case, the motion of the platform is analyzed without considering the forces that affect it, and in the second case, the forces that are responsible for the displacement of the robot are studied. In the end, the equations of the models are presented and contrasted with the real behavior in the laboratory.

Keywords: *Caterpillar Tracks, Differential Drive, Dynamic Analysis, Kinematic Analysis, Non-Holonomic, Service Robots*

1. INTRODUCTION

Although robots are designed and built by humans, there are many differences between the strategies that humans use to interact with the real world, and those that they use and program for their robots [1, 2]. In principle, human beings (at least the majority of the population, those who do not have deep studies in physics or other sciences, and even those who do) do not have a detailed knowledge of the real world, which does not impede for them to act in it appropriately, or other words, intelligently. Human beings use their senses, especially their eyes, to identify the elements of the environment, and coordinate the movement around them, for example, to open a door or move to a particular place [3, 4, 5]. The interaction with these elements makes it possible to open a door or move a chair without the need to know the kinematic and dynamic properties of these elements, hence the qualification of intelligent interaction. The human being can manipulate and develop tasks with a large number of different elements with very little information related to their dynamics, which is considered a fundamental characteristic of its development as a species. Not only this, but he is also able to grasp these elements from different parts of it, change their orientation, and correctly perform tasks with them [6]. This can be observed daily not only in work and industrial environments but also in most of the sports and games that human beings play on a routine basis. By developing these tasks, the human being expands his capacity for action and perception by making these elements his own, and with each new experience, he learns and adapts, improving his manipulation capabilities, precisely the basic characteristic of intelligence [7, 8]. The ability of the human brain to respond to unfamiliar situations from previous situations provides high flexibility and adaptability to unfamiliar situations in the real world.

In the case of robots, the interaction strategies are different, mainly because it is not yet possible to provide them with a similar level of intelligence. The problem is further complicated by the fact that the kinematics and dynamics of robots tend to be highly nonlinear, and by the need to guarantee safe movements for the human being, who is usually at the robot's side [9, 10]. This means that robots are not yet able to adapt to the changes and uncertainties of the environment and its elements, and require to coordinate their movements in the environment, accurately calibrated models that allow predicting their movements in advance, and even with these models, the dynamic characteristics of the environment can produce unpredictable movements for which the machine cannot adapt [11, 12]. Unlike humans, when a robot grips an item at an unknown grasping point, or in a non-pre-established orientation, the kinematics and overall dynamics of the robot are different from those established in the motion models, and therefore it is not possible to perform the task correctly and safely. This consideration is important in the design of a mobile manipulator because although the platform can be analyzed in-depth for the construction of its models, it is not possible to do so for the infinite number of elements and objects with which a robot can interact in different environments, and much more if it must manipulate them. In real applications, a robot cannot be expected to always grasp an object from the same grasping point, so even the manipulation of a single tool becomes a rather complex problem to solve [13]. Humans do not identify the properties of objects before manipulating them, but grasp, manipulate, and identify them throughout these processes, then estimate the ideal grasping point for the development of a task. Incorporating intelligence into a robot in this sense implies developing a control scheme capable of dynamically interpreting the characteristics of the environment, and from there, defining the most appropriate configuration for the task [14, 15].

It is precisely here where research in adaptive control strategies has found a niche [16, 17]. How the problem of dynamic uncertainty of robot configurations has been tackled is by improving the performance of control schemes, providing them with the ability to adapt to different operating conditions, which to some extent depart from the kinematic and dynamic models tuned for the machines [18, 19]. This means that the control schemes are gradually approaching human interaction schemes. These adaptive controls start from the theoretical models but consider a tracking error, which should converge independently of variations in trajectory concerning the expected behavior defined by the models [20]. This implies that despite the increased complexity of the control scheme, it is necessary to know a priori the exact kinematics and dynamics of the robot, hence the continuing importance of its exact development [21]. Furthermore, although the convergence of the exact models derived from the interaction with elements of the environment is not required, the convergence and stability of the combined estimation and control process is guaranteed, which allows high system performance without neglecting safety and performance aspects.

There are still not many tools available for the design of control schemes for robots with uncertain kinematics and dynamics [22, 23]. Much work has been done on calibration methods with the idea of reducing the kinematic uncertainties in the models as much as possible. However, in many cases the matrices change greatly as a function of motion and position, making continuous estimation impossible, and therefore impossible to use in practice. One of the most recent solutions approaches for trajectory tracking when the kinematics and dynamics are unknown is to represent the Jacobian matrix of the robot in a general regression form, and then compute the inverse Jacobian matrix by separating the adjoint and the determinant of the matrix, forming new regressors [24]. This allows and facilitates tracking using direct Lyapunov. However, these strategies constitute an open and young field of research with much work ahead [25, 26].

In this paper, we present the development of the kinematic and dynamic models of a mobile platform with a non-holonomic differential drive designed to assist people in dynamic indoor environments [27]. The development of these models allows for the establishment of a prototype behavior that facilitates the design of tasks, particularly when evaluated on simulation platforms such as Gazebo. This robotic platform was conceived as the locomotive system of the robot, equivalent to a mobile manipulator, so according to its load capacity, it was equipped with four DC motors, each one driving the movement of one caterpillar track [28]. Since these four caterpillars work in pairs, the dynamics of the platform displacement is equivalent to a differential drive. These models are then validated on the real platform in basic path-following tasks and are expected to be useful in the design of navigation strategies in dynamic environments based on reactive behavior [29, 30, 31].

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2. PROBLEM STATEMENT

The ARMOS TurtleBot 1 robotic platform (Fig. 1) was developed as the displacement system for the research group's human interaction robots, which include an anthropomorphic finger manipulator arm, a shoulder and arm robot (both developed by the research group), and a V4 Nao robot from Aldebaran Robotics. The final purpose is the development of a complete platform for the execution of tasks in human service activities, particularly in the care of individuals with medical needs, and surveillance and teaching processes for children. ARMOS TurtleBot 1 is the platform that provides displacement to the system, displacement characterized by the typical features of human indoor environments, highly dynamic, and location constraints for sensors such as GPS (Global Positioning System) and systems such as continuous cloud processing. Other design features include adequate load capacity for interaction platforms and/or the carrying of small objects (medicine, balls, etc.), and the versatility of movement in these human environments.

Figure 1: ARMOS TurtleBot 1 robotic platform

The development of these robotic platforms is costly, as well as their maintenance and operation. As such, it is necessary to have mathematical models that minimize these costs. Adequate mathematical models allow to test and evaluate algorithms on the robot before implementing them directly on the machine. This ensures that schemes that put the robot at risk or simply do not work, are not used on the robot. These models are also important for the adjustment of the robot design since they allow for the evaluation of the performance of proposed modifications. In the same line, it is possible to evaluate the behavior of the robot in different scenarios, which include conditions close to reality, and to repeat these tests many times, which is particularly useful when using control schemes based on reinforcement learning. A final advantage lies in the accessibility of the robot, since there are few existing platforms, with suitable models allowing access to a larger number of researchers, which is of special importance when access to the laboratory is restricted, as has happened recently due to COVID-19.

According to the load constraints (minimum value defined as 10 kg) and motion capability, the ARMOS TurtleBot 1 robot was designed with four 9 V DC motors with geared motor, each with a starting torque of 9.5 kg, no-load speed of 150 RPM (Revolutions Per Minute), starting current of 4.5 A, and nominal working current of 1.2 A (200 mA no-load). These motors have a Hall sensor to estimate shaft position. Each of these motors drives one track according to the configuration shown in Fig. 2. These motors work in pairs, i.e., the same control signal activates simultaneously the two motors on the right side, and others activate simultaneously the two motors on the left side. This scheme not only increases the total torque of the robot but also simplifies its model and control scheme, without losing displacement capacity.

- **Advancing the robot**. Occurs when the motors on both sides advance towards the front of the robot.
- **Right turn**. Occurs whenever the motors on the left side rotate at a higher speed than the motors on the right side.
- **Left turn**. Occurs whenever the motors on the right side rotate at a higher speed than the motors on the left side.
- **Rotation on its axis (right or left)**. Occurs whenever the motors on each side rotate at the same speed and in opposite directions (one side of the robot moves forward and the other backward).
- **Backward movement of the robot**. Occurs when the motors on both sides move the robot backward.

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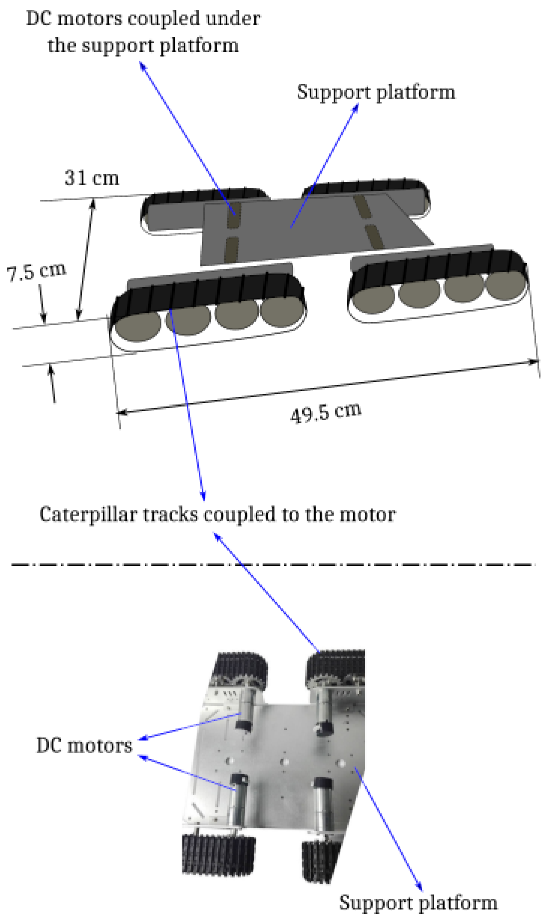

Figure 2: Motor and motion system assembly

A differential displacement system is characterized by having two wheels (or equivalent systems), one on each side, which produces the displacement of the robot thanks to the difference in speed between these two sides. According to the displacement policies defined for our ARMOS TurtleBot 1, its displacement scheme is of a differential type. As in the classical scheme, our robot also has a single velocity on each side of the robot given the synchrony of the motors on each side. Consequently, its modeling can be derived from this classical theory.

Other important parameters when developing the robot models include the construction material (aluminum alloy for the frame, and acrylic on the front and back), its weight (3.8 kg without the interaction robots or other loads on top), a size of 0.50 m x 0.40 m x 0.38 m (length x width x height, the dimensions increase a little concerning the metal frame due to the built-in sensors). It is also important to note that each track has one driving wheel (the one that is coupled to the motor, and is located towards the center of mass of the robot) and three rolling wheels (to increase the stability of the robot). The motors have been identified as M_1, M_2, M_3, and M_4, and are located under the support platform, around the center of mass of the robot (Fig. 3).

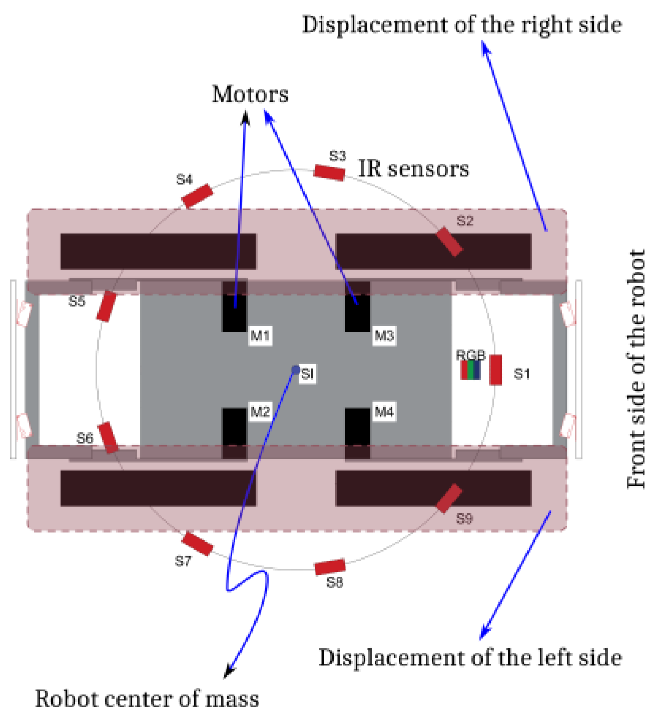

Figure 3: Bottom view of the robot with the detailed location of motors and sensors

As part of the design of path and motion planning tasks, it is required to derive the kinematic and dynamic models of the robot. The kinematic analysis corresponds to the study of the robot motion without considering the forces that may affect it, while the dynamic analysis includes the study of the forces that are responsible for the robot motion.

3. METHODS

3.1 Kinematic Model

The assumed model for the ARMOS TurtleBot 1 robot is shown in Fig. 4. The term nonholonomic means that the robot cannot move sideways, which is one of its motion constraints. As described in the motion policies, the displacements are shaped according to the motion of the motors and tracks, and it is only possible to move forward, backward, or turn according to the speed difference between the sides.

The model also shows that the robot does not undergo deformations due to the construction material and that the displacement is along a horizontal plane. The track width has been identified with the variable L, and as indicated above, the center of mass is located at the SI point with coordinates (x_{SI}, y_{SI}). By construction, this point coincides with the center of the area formed by the four motors, i.e., it coincides with the axis of rotation of the robot (Fig. 3). Following the nomenclature of Fig. 4, the landmark (0, X, Y) identifies the navigation environment, while the coordinates (x,y) identify the position of the robot with origin at the SI point. The angle θ identifies the orientation of the robot concerning the X-axis. Consequently, the set of parameters (x,y,q) describe the initial pose of the robot q, which is written in notation as (Eq. 1):

According to the nonholonomic motion constraint, the lateral displacement systems (left and right tracks) move driven by the rotation of the motors without allowing any slippage. This constraint can be written algebraically as (Eq. 2):

Accordingly, the following set of equations (Eqs. 3 to 7) allow describing the relationship between the linear velocity of the robot and the angular velocities of the pairs of lateral tracks.

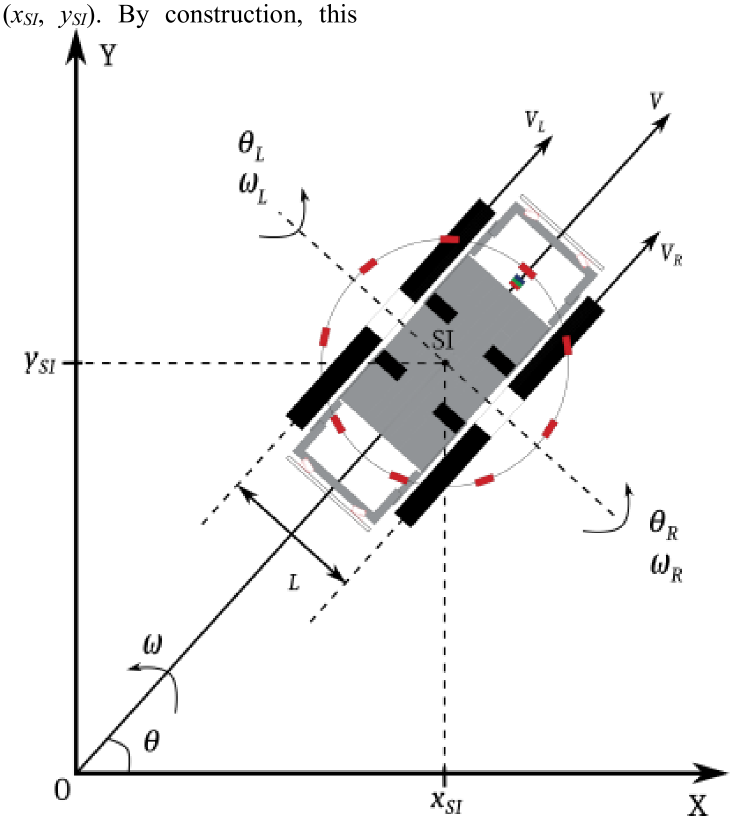

Figure 4: Kinematic and dynamic model of the nonholonomic differential robotic platform with caterpillar tracks

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From the last two equations we have the following model (Eq. 8):

Now, to define the position and velocity of the robot in the coordinates (x, y), as well as its angle of orientation θ with respect to time, the following relations can be written (Eqs. 9 to 11):

Finally, the equations of the kinematics of the ARMOS TurtleBot 1 robot are as follows (Eq. 12):

Where (Eqs. 13 to 15):

These last three equations are updated by Eqs. 6 and 7. Consequently, the kinematic model of the robot is determined by Eqs. 13, 14, and 15. The final kinematic model is given by Eqs. 16 and 17.

In these equations, V_R and V_L correspond to the linear velocities of the left and right displacement systems, each consisting of two motors and two tracks. In coherence with the motion control policies of the robot, these two parameters are used as motion control commands for robot navigation. Similarly, the variables ω_R and ω_L correspond to the angular velocities in the rightward and leftward turns according to the velocity differences between the tracks. The variables V and ω correspond to the linear and angular velocities of the entire platform according to the assumptions shown in Fig. 4.

The update of the control policies according to these variables is as follows:

- **Advancing the robot**: $V_L = V_R$.
- **Right turn**: $V_L > V_R$.
- **Left turn**: $V_L < V_R$.
- **Rotation on its axis (right or left)**: $V_L = -V_R$ (clockwise) or $-V_L = V_R$ (anticlockwise).
- **Backward movement of the robot**: $-V_L = -V_R$.

3.2 Dynamic Model

The motion of the robot described by the kinematics of the previous section is produced by the application of forces on the robot. The forces applied on the robot establish a dynamic model in which their coordinates are related to their derivatives (velocity and acceleration), with the forces and torques experienced by the robot, and with the robot's parameters such as its mass and inertia. These relationships can be described in a non-holonomic differential scheme using the Euler-Lagrangian formulation (Eq. 18):

Where:

- is a symmetric positive definite inertia matrix.
- is the centripetal and Coriolis matrix.
- is the norm-bounded unknown external disturbance vector.
- is the input transformation matrix.
- is the torque vector.

- is the matrix associated with the constraints.
- is the vector constraint forces.

These matrices and vectors are defined as follows (Eqs. 19 to 25):

In these last equations we have that:

- d: is the distance along the robot's axis of motion from the central point of action of the motors to the center of mass; in the ARMOS TurtleBot 1 by design, this distance is zero.
- m: is the total mass of the ARMOS TurtleBot 1 robot.
- I: is the moment of inertia of the ARMOS TurtleBot 1 robot.
- τ_R, τ_L: are the right and left torques of the displacement systems formed by the two lateral tracks.

4. EXPERIMENTS AND RESULTS

It should be clarified that the ARMOS TurtleBot platform is a proprietary development of the ARMOS research group, so there are no mathematical models of this robot in the academic literature. Although most of the similar robots have equivalent functionality, our platform has a tracked displacement system that provides distinctive elements to its real operation. These features make existing models inapplicable to our robot.

To evaluate the fidelity of these models to the actual behavior of the robot, two different types of laboratory tests were performed on the ARMOS TurtleBot 1 robot. The first type consisted of contrasting the robot's motion in a straight line at constant speed against the expected behavior of the model. The second type consisted of tracking a closed path with four 90-degree angles and contrasts the performance against the behavior expected by the model. Some results of these tests are shown below.

4.1 Straight Line Tracking

This test evaluates the forward motion capability by setting the linear velocities V_R and V_L equal in both magnitude and sign. According to the model, the robot should advance in a straight line at the configured velocity. This policy was programmed into the robot, and a series of marks were placed in the environment to measure the deviation in degrees along with the motion (Fig. 5). Different tests were performed for a total distance of 2 m of travel. Although the behavior of the robot closely follows the model, small errors attributable to mechanical parameters were present (Fig. 6). These results are under study for model refinement.

Figure 5: Configuration of the tests for straight-line forward motion of the robot

Fig. 6 shows that a cumulative error is present throughout the robot's motion (average value of 2.1 degrees). This behavior is to be expected and can be adjusted in the model, improving the robot's behavior.

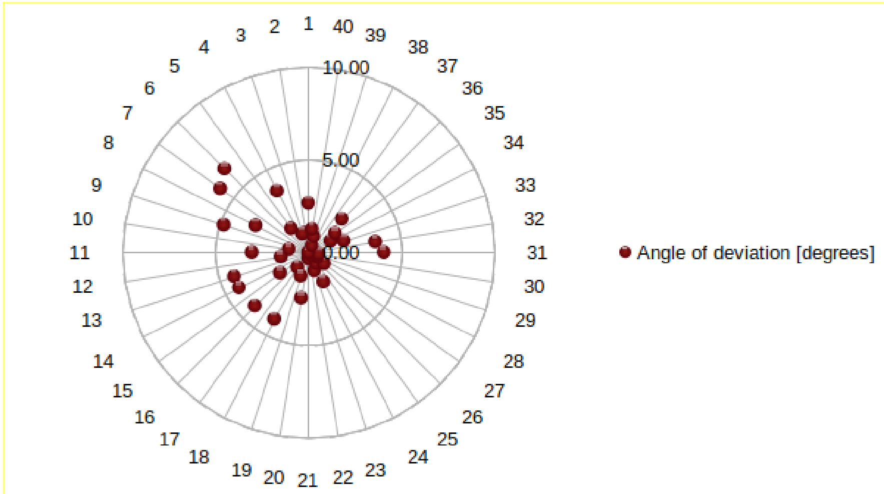
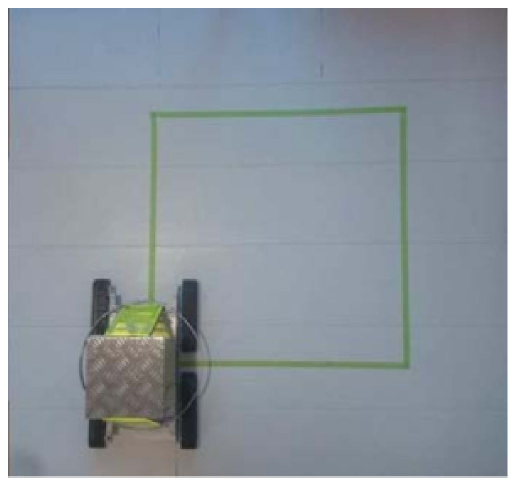


Figure 6: Tracking error in rectilinear advance (40 trials)

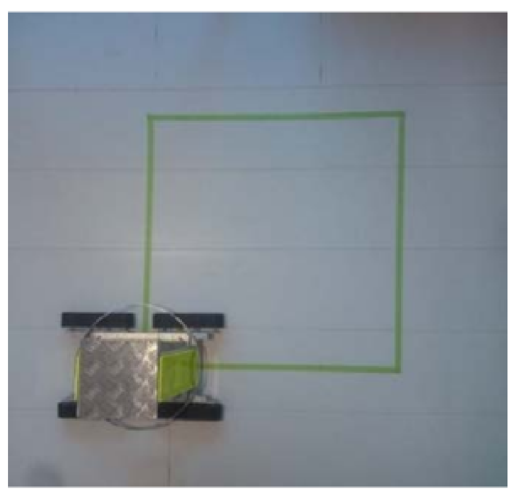
4.2 Rectangular Path Tracking

For this test, a square path with 0.80 m on each side was programmed to be tracked (Fig. 7). As in the first tests of forwarding movement in a straight line, the goal was for the distance navigated to be considerably longer than the length of the robot. Also, in this case, the experiment was repeated multiple times (40 trials in total recorded for documentation), and the accumulated error along all of them was evaluated according to the initial and final positions. The initial position served as a reference, and the errors from this point related to the final position were measured. As in the first tests, a cumulative error was again observed, most of which was centered on the 90-degree turns at each corner (turns around the vertical axis of the robot). The results of the tests are shown in Fig. 8.

The cumulative error in this test causes the square of the trajectory to be redrawn by rotating it at a small angle in the forward direction of the robot (clockwise rotation was used in the documented tests). This offset angle had an average value of 0.62 degrees, and the highest value reached throughout the tests was 1 degree. The distance error (distance measured from the initial reference to the endpoint) had an average value of 0.74 cm. Both values allow to verify the closeness of the real behavior of the robot with its expected behavior by model and again correspond to adjustable mechanical variations in the model.



(a)



(b)

Figure 7: Test configuration for closed trajectory tracking with right angles. (a) The initial position of the tests, (b) final or arrival position of the robot

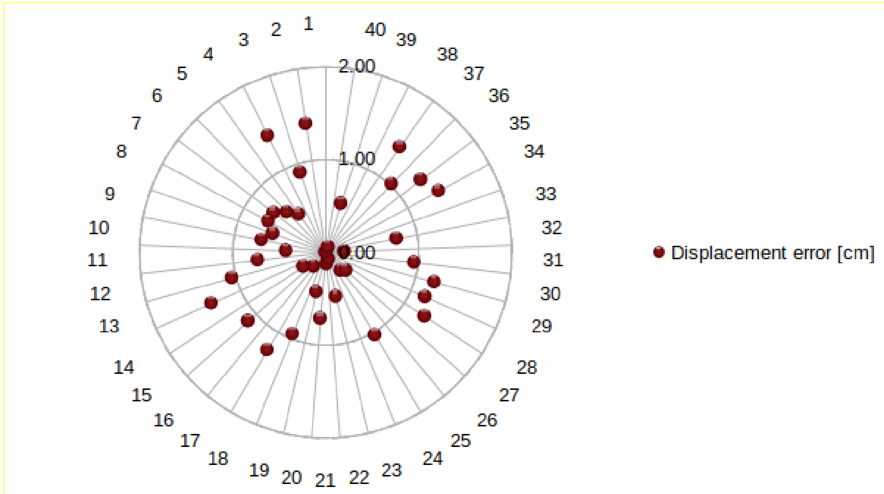


Figure 8: Tracking error in closed motion around a square (40 trials)

4.3 Limitations and Assumptions

These models assume idealized behaviors of the robot elements. They do not consider the inertia of the machine when it is in motion, which causes errors in the turns due to small slips and oscillations. It also assumes the immediate response of actuators, which have a delay time that increases the non-linearity of the response. These are elements that must be analyzed in contrast with the operating conditions of the machine to limit the operating conditions of the model and to propose adjustments for extreme cases.

5. CONCLUSION

In this paper, we have proposed the kinematic and dynamic models for the ARMOS TurtleBot 1 robotic platform. This platform has been developed as a proprietary displacement scheme solution for our service robot prototypes, and currently works as a research system in path planning tasks. Given that this platform is proprietary, and the problems of availability and cost involved in its management by the research group, the objective is to develop mathematical models that describe its behavior, and that can be implemented in simulation tools such as Gazebo. This platform was developed from ideas of versatility in human environments and load capacity according to its final purpose, for this reason, the displacement scheme uses high-performance caterpillar tracks. A total of four caterpillar tracks are used, two on each side of the robot, each of them driven by a DC motor. These tracks have been synchronized in such a way that the two on the right side move synchronously, as do the two on the left side. Consequently, the movement of the platform coincides with the dynamics described by differential systems, in which the movement is defined by the differences in lateral velocity. From this description, the mechanical characteristics of the robot structure, and the robot's considerations, models describing its kinetics and dynamics are proposed. These models are validated during two tests repeated multiple times in the laboratory. The objective of these tests was to verify the behavior of the robot from movements defined from its models. The tests included forward motion in a straight line and consecutive 90 degree turns. In all tests, the average cumulative error was below 1% (0.6% in the line tracking test and 0.9% in the square tracking test) concerning the expected behavior of the models. In addition, the causes of these errors were identified, which allows for adjustments to be made to the models. The delimitation of the robot's operating range is proposed to ensure that its behavior is described by the models, as well as the study of nonlinear behaviors observed during laboratory tests. This characterization is a continuous work of the research group, which allows continuous adjustment of the parameters according to the improvements of the robot.

6. ACKNOWLEDGMENT

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