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DEVELOPMENT OF A CONTROL STRATEGY FOR MOBILE ROBOT NAVIGATION IN UNKNOWN TERRAIN

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Abstract. *This work consists of the development and analysis of a control system for navigation of mobile robots in outdoor applications. A four-wheel-drive robot with sensing based on GNSS (Global Navigation Satellite System) and INS (Inertial Navigation System) estimation is adopted. The main challenge is to create a system that can navigate in a complex environment, such as uneven and rough terrain, as in this condition common sensors usually have its signal lost or changed by interactions with the surroundings. Thus, the objective of this work is to build a control system with simplified but robust behavior. This system is implemented to enable point-to-point programming without the necessity of calibrations according to ground characteristics, even with sudden changes on it. Simulations and experiments are executed, presenting good results by using a single GNSS sensor. Better results can be found in RTK (Real Time Kinematics) mode operation, combining two GNSS devices. Improvements are achievable when accelerometer, gyroscope and compass measurement are combined with GNSS data.*

Keywords: *mobile robots, navigation, rough terrain, GNSS.*

1. INTRODUCTION

The study of navigation techniques for mobile robots is exponentially rising in the last years, mainly because of the increase in power processing of computers used in these applications allied to its cost reduction. However, sensing equipment able to accomplish accurate requests is emergent and still present high costs. A very usual solution to deal with this limitation is to use data from different sensors concomitantly. This is convenient to compensate for errors or delays and to obtain better estimations for a measured variable. Fernandez et al. (2015) present diverse types of research applications on which this idea of sensor fusion is applied. GPS (Global Positioning System), odometry, IMU (Inertial Measurement Unit), compass, LIDAR (Light Detection and Ranging) and camera-based solution are some examples of commonly used sensors in robotics.

However, choosing a sensor is a non-trivial task. Each environment or robot requirement demands different sensor technologies and prices. In outdoor applications, which are the scope of this work, the state of the art in localization involves sensor fusion as a way to create a fully autonomous system (Liu et al., 2017; Wan et al., 2018). Nevertheless, considering a mobile robot in muddy or rough terrain, for instance, the obtained measurements from an encoder or an IMU can be wrongfully estimated. For encoders, this could happen because of the absence of wheel interaction with the soil. For IMU, on the other hand, due to the drift caused by a numerical error. Even using an Extended Kalman Filter in a known terrain, the absence of GNSS data can generate poor estimates for navigation (Pino et al., 2019).

The main motivation for this work is the situation in which all possible sensors can be affected by large errors: a robot moving in a completely unknown outdoor terrain. Generally, mechanical solutions based on wheels, legs or a combination of these designs are adopted to solve the stability problem (Nakajima, 2009; Khusheef, 2013; Pillai and Suthakorn, 2019). By admitting that the robot has already implemented stability algorithms, as shown in the related work of Medeiros et al. (2019), the main problem now is related to navigation, *i.e.*, the robot position and orientation in space along time. Some works emphasize in model the environment by building a map or using landmarks (Lopes et al., 2011; Roldan et al., 2016). Here, the terrain is considered to be initially unknown. Hence, high accuracy GNSS sensors with low-cost antennas were chosen as the main sensors. Even these sensors present some error and uncertainties, however the order of magnitude of the signal is always preserved. While GNSS-only data is useful for a basic control system implementation, inertial data from IMU is useful when the GNSS signal is weak or lost. Thus, the integration of the sensors is necessary to develop a robust control system, as it will be shown in simulations and experiments developed in this work.

2. GNSS SYSTEM

GNSS is a system for position and time estimation all over the Earth's surface. Groups of satellites from diverse countries compose it. The most known system is the NAVSTAR GPS, from the United States. However, GLONASS (Global Navigation Satellite System), from Russia, is another available system. European Union, China, and other countries have also satellites systems, but these are still being constructed or with an operation limited for the region where the country is localized (Kahveci and Can, 2013; Maciuk, 2018).

The wave equation that describes the GNSS signal relates the electromagnetic field, the wavenumber and the index of refraction of the atmosphere. An additional term can be inserted into the equations if the curvature of the Earth is considered (Zhang et al., 2012; Hegarty, 2012). All these parameters directly influence on the signal transmission. The main error source is related to atmospheric conditions and can reach values higher than 5m. However, other problems related to GNSS imprecision are the satellite clocks, the orbital errors, and reflection caused by obstacles. Together, these factors can also promote errors higher than 5m in GNSS measurement (Liu et al., 2017). As it is a problematic task to model the errors in GNSS systems, software and hardware solutions are developed to maximize the accuracy of these sensors. One of them is the RTK (Real Time Kinematics) solution. This technique consists of the phase measurement and correction of GNSS waves. In this case, two GNSS devices must be used, one on the moving system (assumed as a mobile robot, the "rover") and one on a fixed "base", while communication between them is necessary. Figure 1 shows how this communications scheme works.

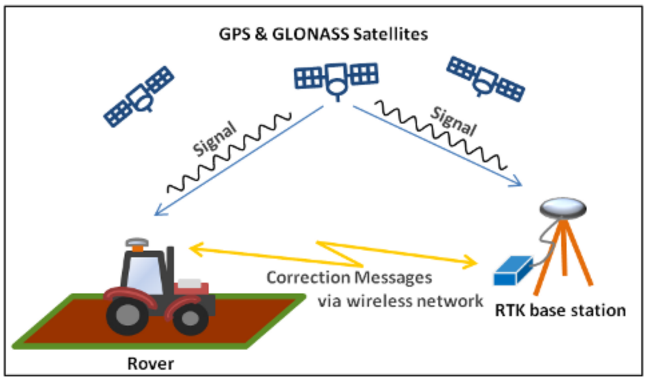
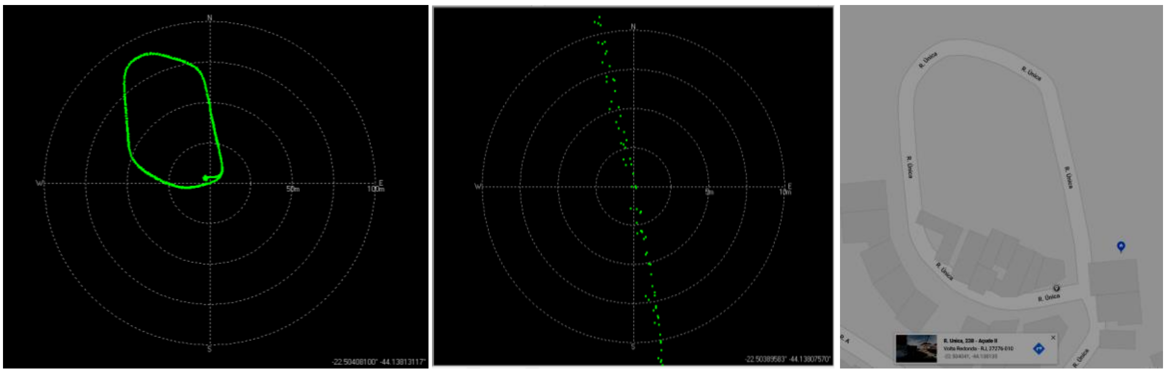


Figure 1. GNSS communication in RTK scheme (Magellan Systems, 2019).

This technology is already in use for precision agriculture and some industrial operations. However, it is usually applied for low-velocity vehicles, involving high costs in the implementation of the sensors. For high vehicle velocities, more expensive solutions can be used, requiring high data acquisition rates. In this work, a system based on low-cost antennas for high precision is used. Figure 2 shows a test executed with the sensors applied in this work, a U-blox C94-M8P application board package, on a vehicle under ideal conditions. The GNSS "rover" antenna is placed on an automobile chassis for a nine-lap test with three different velocities. Figure 2(a) shows the overlaid results of the nine experiments, while Fig. 2(b) shows a zoom in the image where it is perceived that the GNSS errors stabilized in values smaller than 1m. Figure 2(c) is a representation of the streets in which the tests occurred, extracted from Google Maps. The total elapsed trajectory is about 2km. In the tests, data acquisition was performed adopting a 5Hz rate and no "base" antenna was used, which demonstrates that the sensor already presents a good accuracy for future RTK experiments even without the aid of the base data.



(a) (b) (c)

Figure 2. Outputs of the GNSS sensor tests: (a) overall view, (b) zoomed detail, and (c) Google Maps data for comparison.

3. ATTITUDE CONTROL

The mobile robot especially developed for this work is a fully autonomous four-wheeled drive system. Its main objective is to navigate on unknown terrain. A control algorithm is necessary to guarantee the objective accomplishment. An initial strategy to solve this problem is to adopt a proportional or a derivative-proportional control that can be used in combination with the output of an EKF (Extended Kalman Filter). For complex tasks, the main interest is to have an algorithm able to move the robot from an initial for a final point independently of the trajectory. This will automatically occur if there are impossible trajectories to move the robot straightly to its desired goal. However, the priority is to move the robot in a line that connects the initial and final points of the trajectory. The control algorithm then has to correct the movement only in case of external disturbances acting above the system.

Figure 3 shows the variables involved in the problem. In this case, corrections in robot velocity are not considered, only in position and orientation. The variable d is the distance between the robot and its desired trajectory. D is the distance between the robot and the final point of a trajectory. The angle α describes the trajectory while β describes the desired robot orientation. In an ideal condition, the error d is equal to zero and β is equal to α. In this case, Eq. (1) can describe the control law.

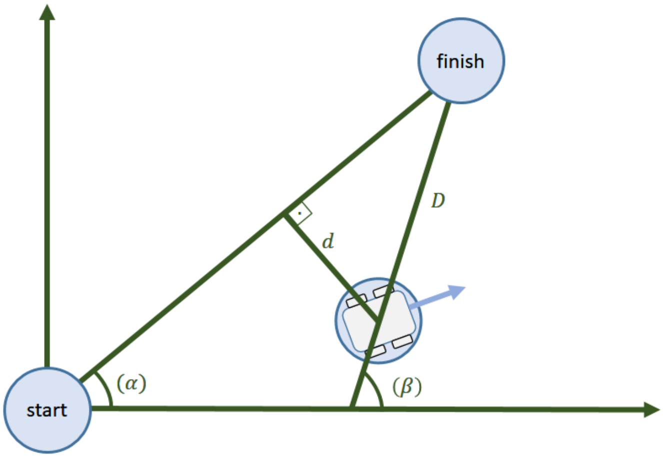


Figure 3. The scheme used to create the control algorithm.

$$\beta = \alpha \pm sin^{-1}(d/D) \tag{1}$$

The robot linear velocity is set to 1.5m/s and the control law is responsible for variations in the angular velocity. The maximum angular velocity is set to 1rad/s. The control algorithm is implemented in Python language and it is also operational with ROS (Robot Operating System). The hardware used to control the mobile robot is based on an NVIDIA Jetson TX2 Developer Kit and a motor controller Roboteq XDC2460.

4. SIMULATIONS

Before the experiments, a set of simulations was performed to evaluate the system behavior and its maximum accuracy under the dynamical requirement. The simulations are based on MATLAB Sensor Fusion and Tracking Toolbox, which uses an Extended Kalman Filter for state estimation. The simulations considered only the robot sensor's characteristics or properties, as in this step the control system is not evaluated. Real-world interferences are also simulated and a simplified case was considered, based on level terrain. This condition is useful as it can be considered a parameter to future comparisons.

A circular trajectory for tracking is adopted, with a radius of 10m. The initial latitude, longitude, and altitude are the same used in experiments with the mobile robot. The sensor fusion combines IMU data (orientation) with GNSS data (position). The IMU frequency is set to 100Hz. This frequency reproduces the data sensors used in experimental hardware, a Pixhawk PX4 2.4.8. The GNSS frequency is set to 1Hz (RTK mode activated) and 5Hz (RTK mode deactivated). In RTK mode, the GNSS accuracy is 0.1m, while in other cases it is 1m. The linear velocity is set to 1.5m/s and the initial yaw angle is not aligned to the trajectory. The misalignment is implemented to verify the robustness of the estimator. Roll and pitch angles are considered null. The GNSS decay factor, which depends on atmospheric conditions, is set to 0.5. The end-to-end position RMS (Root Mean Square) errors are calculated and the results are shown on Table 1. This table also presents the maximum absolute error in trajectory simulation when RTK mode is active and when it is not.

The minor errors in RTK mode compared to a case with only one GNSS were expected. Even the GNSS data acquisition frequency, in this case, is lower, the corrections from the base can improve the localization and a centimeter-level accuracy becomes possible. Figure 4 shows the behavior of the errors during a trajectory tracking with RTK mode active. The major error is found at the beginning of the movement because of the initial orientation used. For error reduction, IMU and GNSS devices with higher frequencies should be used. As the sensors here used are considered low-cost, the estimation is limited. If the maximum velocity of the robot is considered (7m/s), the robot runs about 7m without GNSS feedback at 1Hz of data acquisition frequency. Because of this limitation related to hardware, the improvement proposed in the attitude control is highly necessary.

Table 1. Mean and maximum absolute errors for X, Y in trajectory tracking.

RTK	GNSS Frequency (Hz)	GNSS accuracy (m)	RMS error (m)		Maximum absolute error (m)	
			X	Y	X	Y
ON	1	0.10	0.52	0.26	1.87	0.79
OFF	5	1.00	1.06	0.74	2.82	2.12

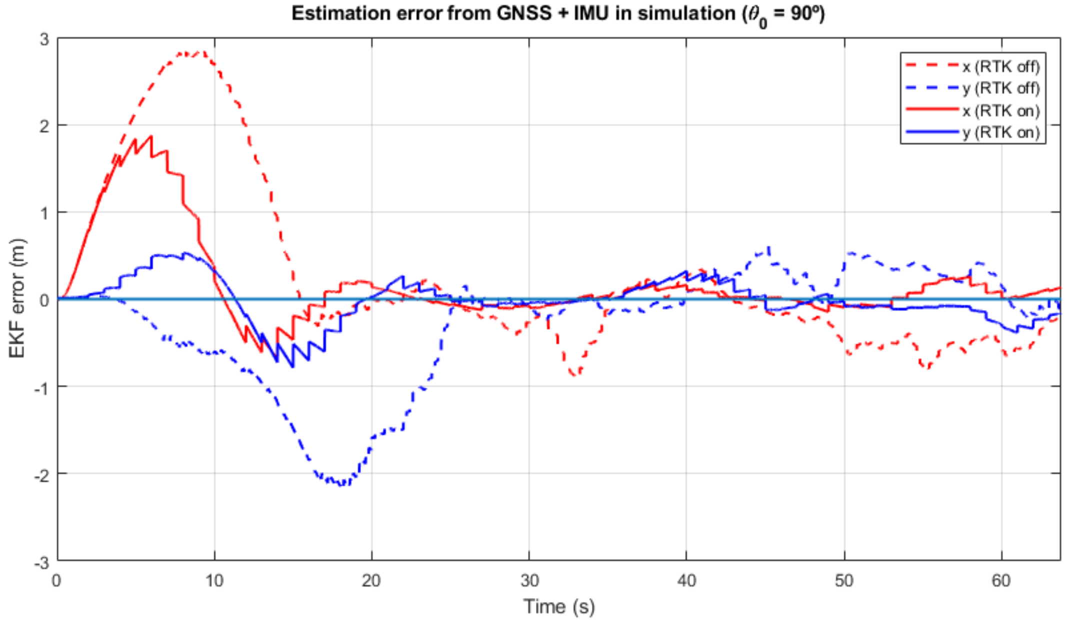


Figure 4. Errors obtained during the simulations considering the use of RTK GNSS.

5. EXPERIMENTS AND RESULTS

The experiments were performed in several steps. In the first moment, the mobile robot is driven using an RC (radio-controlled) device following lines and markings on the floor. This procedure is executed by using both RTK and single GNSS mode. The objective to be achieved in this step is basically to evaluate the GNSS devices used in the robot, according to its accuracy and repeatability. The lines followed by the robot determine the real tracked trajectory. The GNSS "rover" measurements determine the estimated trajectory. The same GNSS devices are used as "base" to previously configure the GNSS coordinates on the terrain. The lines formed between the initial and final point of each path is the desired trajectory.

On the second step, the control algorithm is implemented and the robot is used in autonomous mode. The control here applied is especially devoted to navigation in complex terrains, but the initial tests are performed in ideal conditions. First in a leveled terrain and with initial orientation aligned to the trajectory, later with a misalignment. Similar to the simulation case, it is necessary to verify how robust the proposed control is. Finally, experiments were performed with obstacles put in robot trajectory, to verify how it is the control behavior for real case application. The robot used in the experiments is the modular four-wheeled drive robot shown in Fig. 5, built at the Pontifical University of Rio de Janeiro (PUC-Rio) Robotics Laboratory (LabRob). Its main characteristics are shown in Table 2.

As the main objective here is to move the mobile robot between two points using an arbitrary trajectory, distance sensors for obstacle avoidance and vision systems were not implemented. The GNSS coordinates that describes each point of the trajectory are previously set. The accuracy reached in this setting depends on the time elapsed after a "survey-in" process. This procedure is performed to find the absolute position on the Earth's surface with good accuracy. The sensors used in this work can reach a centimeter-level accuracy if a long time of measurement is used. Based on experiments, in a half-hour, accuracy about one meter was reached. In five hours, a less than 0.5m accuracy was possible. Better accuracies can demand more than an entire day, as the standard deviation becomes smaller with larger samples. The good estimation of these fixed points is essential for robot navigation, especially in RTK mode, but sometimes the procedure cannot spend a long time to be executed and an intermediary accuracy is accepted.

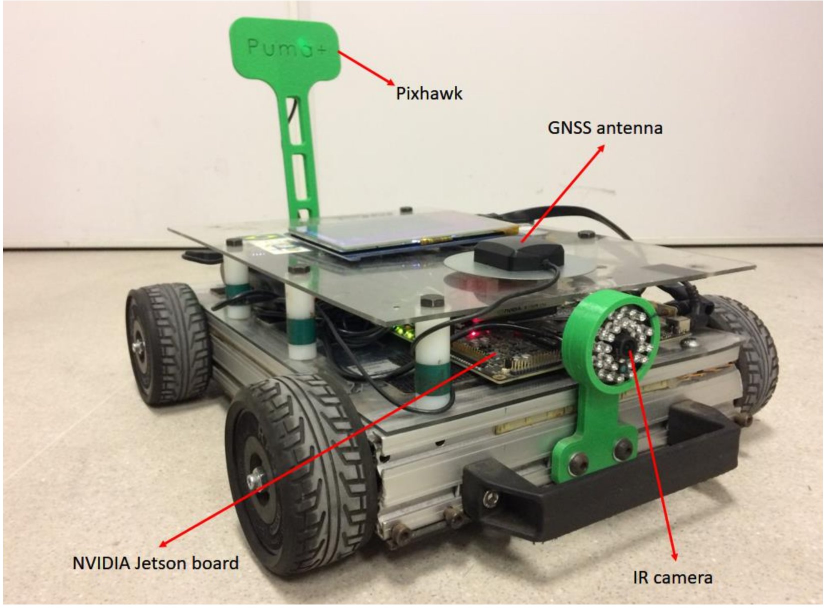


Figure 5. The mobile robot used in experiments.

Table 2. Robot's characteristics.

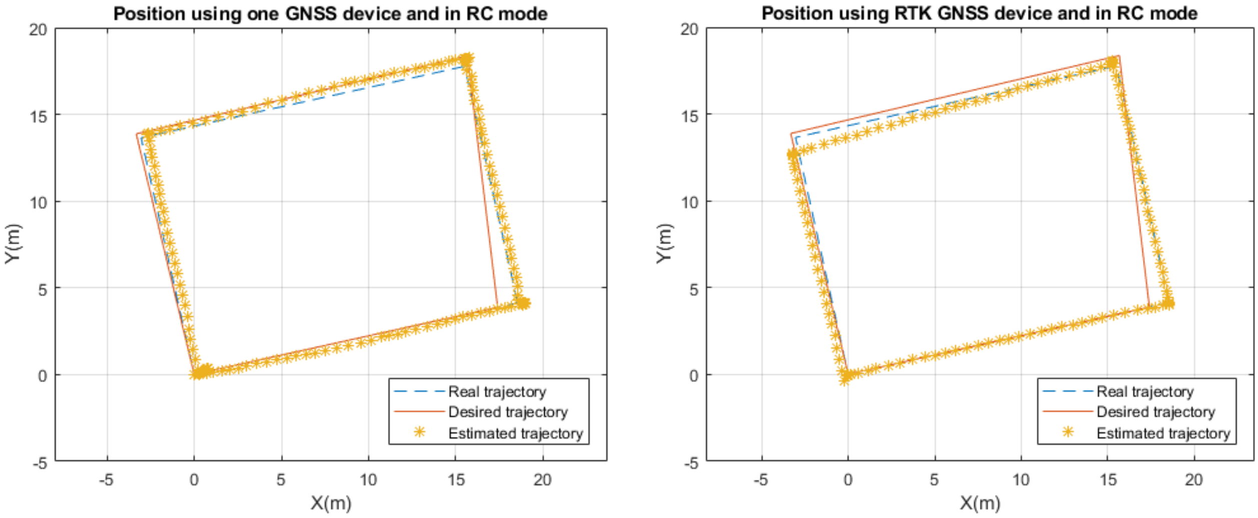
Length (m)	Width (m)	Height (m)	Weight (Kg)	Payload (Kg)	Speed (m/s)	Steering
0.50	0.40	0.36	17.05	>100	7	Skid

However, the error related to the "base" GNSS configuration is not the only problem found when measuring GNSS signals. Terrain unevenness and the robot velocity are two factors that have to be considered when high precision is desired. The unevenness can contribute to unexpected deviations from the desired endpoint, while the high velocities restrict the GNSS position estimation rate. As these errors cannot be undervalued, the navigation algorithm is intentionally implemented with an error threshold of 1m. This value is based on two pieces of information. First, the absolute position measurement error acquired in the GNSS base stations during the survey in process is of the order of 1m. Second, using the fact that under a frequency of 1Hz the robot can run more than 1m without GNSS feedback. Consequently, if the robot is 1m from its goal, in a circular zone, the control system will recognize that the robot accomplished its trajectory and the algorithm is stopped.

Figure 6 shows the GNSS data related to radio controlled tests. The point (0,0) is the beginning of the trajectory, which continues counter-clockwise. In Fig. 6(a), without RTK, it is possible to observe that the real trajectory followed by the robot is very similar to the estimated trajectory. Mean errors and maximum absolute errors are below 1m. Fig. 6(b) presents a very similar behavior. In this case, the RTK mode was activated. An interesting result can be found in the first part of the trajectory in Fig. 6(b), in which the maximum achieved error is 0.10m. By comparing these data with the simulations with sensor fusion RTK + IMU, it is noticeable that the influence of the IMU in this specific case is minimal. In experiments without online control, both GNSS-based methods presented good results.

A small deviation is found around the third point of the trajectory in Fig. 6(b). However, this deviation is not significant, as it is smaller than the error threshold of 1m. However, a problem found in the experiments is related to a discrepancy in the second point of the desired trajectory. After the survey-in process, the real and the desired trajectory should be equal. In this case, there is a distance of 1.18m between the two points. As stated, the survey-in process applied in this work has a standard deviation of 1m. Therefore, the discrepancy is 0.18m higher than the acceptable threshold. It is a small value, but it is also an indicator that the survey-in process has to be correctly performed to avoid error propagation. Another source of error, in this case, is related to the robot driver in RC mode. The estimated error in this situation is ±0.10m concerning the real trajectory. The survey-in error and the driver error are added to the GNSS errors in the estimated trajectories shown in Fig. 6. These initial results are similar to the results shown by Pino et al. (2019), which proved that even the GNSS without odometry feedback can provide information about a performed trajectory if an online control is not used.

Conversely, the main problem in this work is not related to localization itself. It is a problem of autonomous navigation in unknown terrain. This kind of system has to achieve its final position with the best accuracy in real-time and using any possible safe trajectory. This control can also contemplate adverse situations, such as navigation in the condition of wheel slippage, with obstacles or in dynamical environments.



(a) (b)

Figure 6. GNSS trajectories: (a) RC mode without RTK; (b) RC mode with RTK.

A first experiment based on real-time control for the trajectory accomplishment can be performed without the use of an IMU, as performed in Fig. 6 for the offline situation. Figure 7 shows the robot behavior in this case. The error achieves a value of 2.90m in comparison with the real trajectory that the robot has to perform. The GNSS signal errors are not corrected on able time because of the GNSS data acquisition rate, and the controller gains are not enough to correct the direction. The desired trajectory is not explicitly shown because in this case, it is coincident to the real trajectory. The final error in Fig. 7 is small, but it is an exception. Table 3 shows the measurement error in the robot's final positioning in a set of tests. Based on this table, it is possible to observe that the GNSS accuracy for real-time tasks is problematical. Besides, based on the values in Table 3, it is a conclusion that the use of only GNSS data is not robust and the use of an IMU becomes essential.

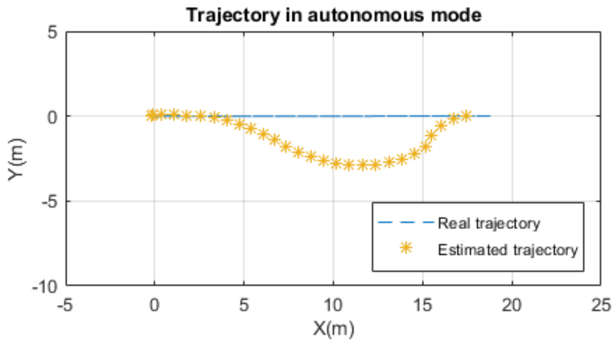
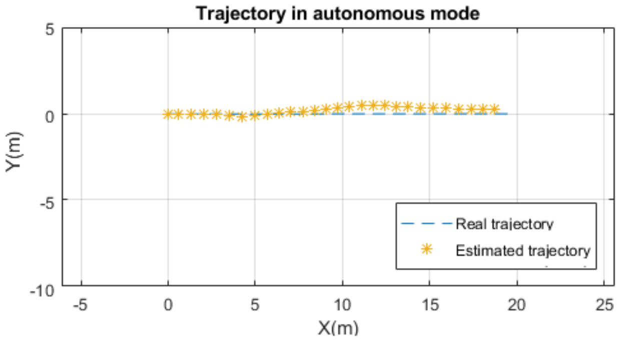


Figure 7. Real-time control without IMU feedback.

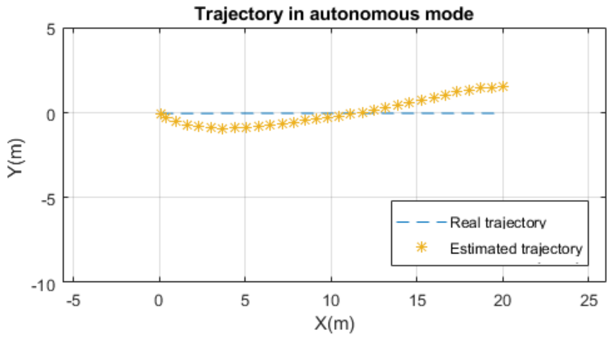
Table 3. Measured error in experiments based only on GNSS data.

Error (m)												Mean (m)
1.82	2.41	3.00	2.87	1.95	1.71	1.48	1.61	2.98	1.96	2.53	2.19	2.21

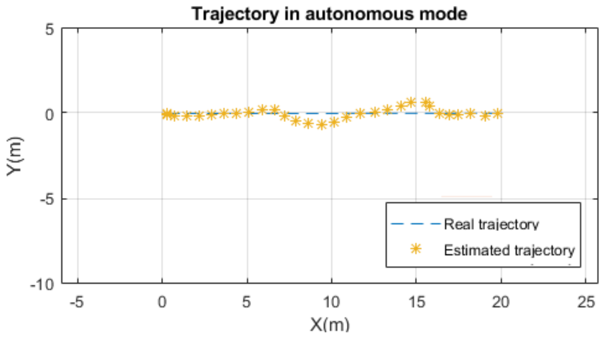
Figure 8 shows the results for the control law implemented, which is based on Eq. (1). In Fig. 8(a), an ideal condition is implemented, *i.e.*, the robot has to track a straight line using an initial orientation of the trajectory. In this case, the maximum error achieved during the trajectory is 0.46m. Moreover, the error was always smaller than 1m, the programmed error threshold. In Fig. 8(b), to test the control robustness, the initial orientation of the robot was changed to –45º from the trajectory direction. In this experiment, the robot was able to correct its orientation according to GNSS and IMU data and performed a smooth correction curve. The final error, in this case, was 1.59m, thus 0.59m above the programmed threshold. Figure 3(c) considers the initial orientation aligned to the robot's trajectory. However, in this case, perturbations are inserted employing external and arbitrary forcing in the robot chassis. These perturbations are introduced when the robot was at 6m and 12m from the beginning of the trajectory. Once again, the robustness of the control is experimentally demonstrated, since the maximum error in this case is only 0.71m. Even in other similar tests, the worst measured error was always near the implemented threshold.



(a)



(b)



(c)

Figure 8. Control based on single GNSS and IMU estimation: (a) test in ideal conditions; (b) initial orientation of –45º; (c) perturbations inserted during the tracking

The previous results demonstrate that the robot used in this work and the implemented control can achieve, even with low-cost sensors, trajectories with good accuracy in outdoor terrains. The experimental results can be compared with the simulations previously shown in this work. The trajectory from Fig. 8(c), which considers the control submitted to perturbations and without the RTK activation, has smaller errors than the simulations that considered RTK mode with IMU fusion. For the RTK implementation, this work presented results with similar accuracy to Munoz–Banon et al. (2019). In addition, here the simplified control was able to perform all tests without interruption problems and using basic hardware more than 10 times cheaper than in Munoz–Banon et al. (2019). Moreover, the control used here was also tested under higher speeds, up to 3m/s; in this case the maximum final measured error registered was 2.33m. This is a comparatively good result for such a high speed, since the robot in this condition can run more than 3m without GNSS feedback. In this high-speed case, better results could be achieved with the same hardware if the robot speed was considered in the robot control law. The RTK use could also improve the precision in general tasks. LIDAR and cameras could also be implemented to improve the local navigation, while GNSS and inertial sensors would be responsible for the global navigation system.

6. CONCLUSIONS

This work presented the development of a control strategy for navigation of mobile robots in unknown terrains. Initially, a GNSS system was proposed. Simulations were performed to verify the behavior of the GNSS system. The simulations showed how an Extended Kalman Filter based on inertial sensors can influence the accuracy of the mobile robot. Experiments were performed to verify the behavior of the GNSS and the control system. When the robot was radio-controlled, GNSS sensors were able to reasonably estimate the robot localization after the positioning. Similar results were also found for the autonomous system, especially under conditions of external perturbation. New strategies should be developed to improve robot navigation in autonomous mode, to guarantee that it can run in complex terrains using low-cost devices. Moreover, the use of different sensors, such as cameras, could potentially contribute to advances in this area. The integration of the navigation control algorithm with inertial algorithms for stability would also be desirable, as it could improve the behavior of tracking tasks using mobile robots in rough terrain.

7. ACKNOWLEDGMENTS

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