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***Abstract*—The problem of multi-robot research is of great dependency on the platform used to conduct the experiments. Various commercial available research support robotic platforms are used in different labs worldwide. However there is always a compromise between cost and reliability. Thus the need to develop a low-cost reliable multi-robot platform urged. In this study, a low-cost heterogeneous mobile robots platform is proposed, based on integrating multiple commercially available components, and compensating for their uncertainities and errors through control algorithms. Four vehicles are developed, two wheeled differential drive based, and two tracked vehicles. A wireless radio frequency full duplex communication channel is implemented to provide a reliable channel for control and feedback between the robots and the ground station. An overhead camera is used to provide a real-time visual feedback for the robots. A computer vision algorithm is implemented for tracking multiple robots simultaneously and recording their trajectories for further analysis. Multiple sensors are integrated on-board; Inertial Measurement Unit, encoders and infra-red sensors. A test scenario is conducted to validate the feasibility of the developed platform. Results achieved are promising, and opens the door for further research efforts down this road.**

Keywords: Mobile Robots, Multi-Robot System (MRS), indoor, platform, heterogeneous.

I. Introduction

Research in the field of mobile robots have been advancing at a growing rate during the last few decades. Mobile robots have embarked many of the application fields such as security, search and rescue, demining, and even education [1]. In scientific applications, researchers usually rely on mobile robots to validate their theories and hypotheses about several applications that are applicable to real world environments. To be able to further build on these results, a robust robot testing platform is required for testing the developed algorithms.

Mobile robots have many factors to be considered when under study, one of which is the locomotion of the robot. The type of locomotion is the answer to the question: how can the robot move around in its environment. Several locomotion techniques can be used for mobile robots either aerial or ground, and even for the ground several choices may be made, either wheeled, legged or hybrid locomotion systems [2].

One of the highly used techniques is the wheeled locomotion system. Generally, Wheeled Mobile Robots (WMR) are characterized by their efficiency on smooth and firm surfaces, as well as their ease to control through the management of the actuators to follow their desired trajectory [3]. Tracked vehicles as well are widely used due to the fact of their differential drive mechanism that enables them to achieve almost any desired pose, and their high stability.

Several commercial products have become available based upon mobile robots advances, serving different markets. Some products such as the Lego Mindstorms [4] became commercialized for the purposes of education and research support, and are widely used nowadays. On the other side of complexity continuum, robotic platforms such as the Pioneer and Khepera robots [5] exist. They provide reliable performance that can be depended upon, however it comes on the price of cost and complex libraries. Somewhere between both existed some commercially available robots at reasonable prices such as the Roomba robot [6]. The continuum of complexity, price and reliability spread widely.vspace3pt

Some research efforts have been directed towards developing low cost platforms relying on some of the commercially available robots such as [7], in which the Roomba robot was used as the main platform and other modules were assembled on top of it.

In [8], researchers developed a mobile robot platform to be used for security applications. The developed platform was tested in several scenarios, and results reflected the ability of the mobile robot to perform with satisfactory performance in motion control, positioning, patrolling and monitoring the environment.

A module based platform for mobile robots is developed in [9]. The system contains many modules that communicate with the master module using I2C interface. The main controller of the robot system is industry personal computer that can display the status of the different modules. Modules are on plug-and-play basis; easily added or removed.

Another control platform for mobile robots is developed in [3]. Control of the Roomba robot was developed using ROS (robot operating system), through the velocity vector references. In that study, a kinect sensor was integrated into the system for monitoring and remote control. The framework proposed enables the control of the robots' movement using the spatial references extracted from the environment through the kinect sensor.

Recently, a cooperative heterogeneous mobile robotic platform and framework was proposed in [10], in which a framework for controlling a heterogeneous wireless robotic network consisting of aerial and ground vehicles was proposed. The systems used are characterized by different dynamics and thus a challenge to control them is imposed. The scenarios used studied a decentralized connectivity strategy, as well as an autonomous communications relay in GPS-denied environments. The proposed methodologies are validated through numerical simulations and experimental results. It is worth to note that this system suits both indoor and outdoor applications.

The rest of this paper is organized as follows, in section 2 the proposed experimental platform is discussed in details. Section 3 illustrates the experiments conducted procedures as well as the metrics used in analysis. Section 4 presents the results achieved. Finally, Section 5 concludes this study with conclusions and future endeavors.

II. Experimental Platform

In this section, details of the different modules integrated on each of the robots are discussed. The developed platform includes a testing arena of dimensions 2 meters in both length and width, used for different tests and scenarios. Four heterogeneous mobile robots are developed in this study; two wheeled differential drive and two tracked vehicles, to have variety in the locomotion system, shown in figure 1. An overhead camera is fixed on top of the testing arena to provide visual feedback required by the computer vision algorithm for tracking the robots' trajectory.
The base of the robots used are of the commercially available platforms for both the differential drive as well as the tracked vehicles. Actuators used in such robots are DC-motors (with encoders for the tracked vehicles only). All vehicles are powered by Lithium-Polymer (Li-Po) batteries of 7.4 volts and 1600 milli-Ampere-hour. Several modules are implemented on each robot, as shown in figure 2. Details of the different modules integrated on both types of robots are discussed next.

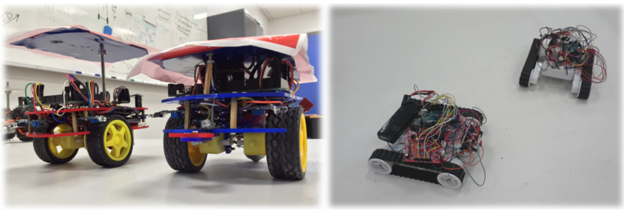

Fig. 1. The developed Multi-Robot System (MRS)

A. Sensors

In order to compensate for the low reliability of commercial available robots, different sensors are used on each type of robot to provide a type of on-board controller. Through integrating the developed algorithms with the sensors readings, the reliability of the robots to follow a desired trajectory improved.

1) Inertial Measurement Unit: A 6 axis Inertial Measurement Unit (IMU) is used along with the suitable filter to be able to estimate the heading (orientation) of the robots accurately. The IMU is composed of two types of sensors; accelerometers and gyroscopes. The data from both sensors is fused together to evaluate the most accurate information about the heading angle.
Accelerometers measure physical acceleration relative to the free-fall along one dimension. A tri-axial accelerometer unit is used, and as the vertical component of the acceleration value

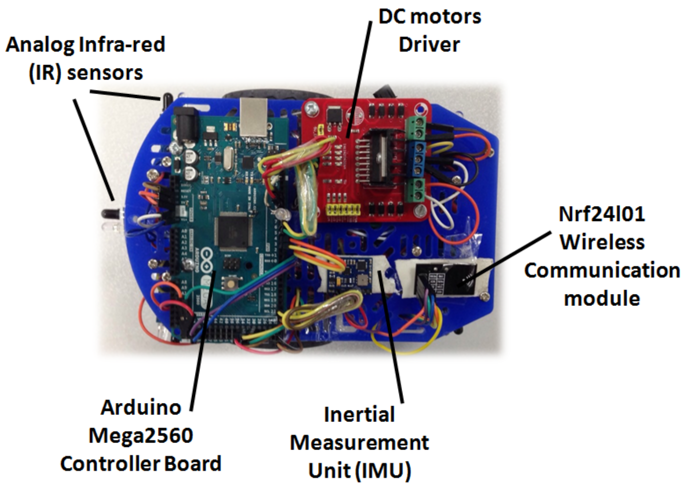

Fig. 2. The different modules implemented on the robots

for flat objects must be equal to the gravitational acceleration $(9.8m/s^2)$, it is possible to compute the tilt angle of the sensor and accordingly the robot's angle.
Gyroscopes can sense angular velocity along one rotational axis. Through integrating the rates from the known initial angle, the heading can be computed.

The measured data from the sensors needed to be filtered. The Complementary filter [11] is used for this purpose, as it provided a good trade-off between the readings of both sensors; gyroscope on the short term, and accelerometer on the longer term.

2) Encoders: Encoders are used to translate the motion either rotary or linear motions into two or three channel output. In this study, rotary optical quadrature encoders are used to compute the robot's speeds of each wheel to be able to estimate any rotation effect and try to compensate for it.
The problem of bouncing of the signal is one of the main problems faced in this sensor. Two possible solutions can be used in this regard; either software debouncing or hardware debouncing. In this study, the software debouncing solution is used through the implemented algorithm.
Using the reading from the encoders, the angle of the robot can be evaluated. Through approximation of the robots to be as a square of side 23 cm, that fits inside a circle. Thus the distance moved is equal to the arc length of rotation facing the angle (θ). The simple equation in (1) is implemented in the codes for this purpose.

$$ArcLength = \frac{r\pi\theta}{180} \tag{1}$$

where r is the half the diagonal of the square, and θ is the desired angle of rotation. The desired angle is computed from the arctan of the differences of the coordinates in X and Y. where a +ve value indicates clock-wise rotation, and a -ve sign indicates counter clock-wise rotation.

3) Infrared Sensors: In order for the robots to be able to successfully navigate in their environment, they need to be equipped with multiple sensors, spatially distributed on the robot surface, and facing different directions. Infra-red sensors are used for this purpose. They provide feedback to a

certain algorithm implemented on the on-board controller for successful maneuvers. Each robot is equipped by 5 sensors (1 Front, 2 Front-Sided and 2 Back-Sided).
The reason for having two sensors on each side is to successfully execute the logic of the algorithm used which helps in the getting throw phase of the car algorithm.

B. Onboard controller

On each of the robots, an on-board controller is implemented, taking control of all the local decisions executed on the robot, from changing its speed, maintaining the orientation, and sending information to the ground station.
The speed of the robot is controlled by this on-board controller via a Pulse Width Modulation (PWM) signal sent to the dual H-bridge driver connected with the motors.
In this study, the Arduino development boards [12] (shown in Figure (2)) are used as the low level controller. Arduino recently became a commercially available widely used controller platform in multiple applications, and provide acceptable reliability for moderate complexity applications.

C. Wireless Communication Module

In order to be able to provide a reliable communication channel between the robots and the ground station; a two way wireless communication channel is used.
The Radio-Frequency (RF) modules working at high frequencies are used to achieve this task. The nRF24L01 modules [13] operate at 2.4 GHz, and provide a simple full duplex channel of communication between the different robots and the ground station. Five modules in total were used, one for the ground station, and one on each of the robots.

D. Computer Vision Module

In order to be able to track the trajectories of the different robots during their motion in the arena to achieve their goals, a robust computer vision algorithm is developed. Based on acquired images from an overhead camera fixed on top of the arena providing a continuous real-time feedback of the robots, the computer vision module is implemented.
Various tracking techniques are used in different applications, according to the nature of the experiment. In this study, a robust algorithm based upon color tracking integrated with a continuous euclidean distance based estimator is developed. For each time sample, the acquired images are analyzed, and the centroids of the robots in motion are evaluated, then a state estimator is used based upon the euclidean distance between the detected centroids in each two successive frames is executed. According to this output, the appropriate centroid is assigned to each robot. The pseudo code for the computer vision algorithm is presented in algorithm (1).

E. Controller Design

In order to have a reliable performance of the robots, an on-board controller is implemented on each of the robots. The controller used is PID controller, implemented in its discrete form as described in equation (2). The controller is implemented in the on-board controller to maintain a certain orientation of the robot, based upon the reading evaluated

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Algorithm 1: Computer Vision tracking Algorithm

while *There are robots moving in the arena space* **do**
- **Capture** new frame from the overhead camera
- **Convert** image from RGB to HSV color space
- **Select** the Saturation plane
- **Threshold** the S-plane using a preset threshold value
- **for** *Each detected region in the thresholded image* **do**
  - Compute the centroid of this region (position in X and Y)
  - Evaluate the euclidean distance between the detected centroid and all from previous frame
  - Assign for each robot its current centroid

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from the IMU or the encoders.

$$x_n = Ae_n + Be_{n-1} + C(Int_{prev}) \tag{2}$$

$where$,

$$\begin{aligned} A &= K_p + 0.5K_iT_s + K_d/T_s \\ B &= 0.5K_iT_s - K_d/T_s \\ C &= K_i \end{aligned}$$

where, Kp, Ki and Kd are the proportional, integral and derivative gains of the controller respectively. While T_s is the sampling time of the controller. The parameters of the PID controller are evaluated experimentally for each type of the robots.

III. Experimental Procedures

In order to validate the developed platform, a multi-stage test scenario is conducted. The test scenario conducted is described in the upcoming sub section in more details, followed by the evaluation metrics used to evaluate the reliability of the produced results.

A. Test Scenario

The four developed robots are tested in a simple scenario to validate their ability to achieve a certain task related to coping with uncertainities in the environment as well achieving their desired goal or objective.
The four robots are placed in the test arena at random initial positions, in which they had to reach a certain goal with its coordinates predefined. The environment embarked is of unstructured dynamic nature, meaning that the robots had no information about the obstacles in the environment. And also they had to deal with the other moving robots in the environment, thus dynamic.
Relying on the computer vision feedback module, the positions of the robots during the experiments are recorded and plotted. Experiments are conducted multiple times with different initial conditions to study the robustness of the proposed platform. The scenario experimented is shown in figure 4.

B. Evaluation Metrics

Several metrics are widely used to evaluate the reliability of the performance of the mobile robots platforms and tasks. Some are based upon error from reference trajectories, while

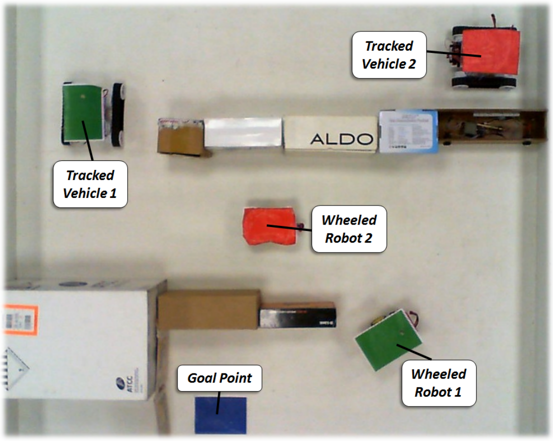

Fig. 3. The test scenario conducted

others assess based upon the time consumed in achieving the task.
In this study, one of the most important metrics is used; being the error between the reference trajectory and the actual trajectory. This reflects how accurately can the robots used track a given path

One of the most important metrics used is the error between the reference trajectory and the actual trajectory. This shows how accurately the robots can track a given trajectory. The ideal trajectory is produced through a simulator for the robots motion. Instead of evaluating each state in the pose of the robot $[x, y, \theta]^T$ independently, the absolute euclidean distance defined in equation (3) was chosen as an error metric.

$$error = \sum_{i=1}^{n} \left(\sqrt{(x_{i,ref} - x_i)^2 + (y_{i,ref} - y_i)^2} \right) \quad (3)$$

Where (n) is the total number of points considered in computations. While $(x_{i,ref}, y_{i,ref})$ are the ideal x and y positions at a given sample (i) evaluated by the simulation software, and (x_i, y_i) are the actual positions of the robot evaluated from the computer vision module.

IV. Results

The developed experimental platform is tested in the prescribed scenario. The overhead camera is used to track the trajectory followed by each of the robots. The scenario under study was conducted multiple times to check the robustness of the developed platform.
The shots of the robot motion at different timings in one of the tested scenarios is shown in figure 4. As can be seen the overall execution time of the mission is almost 60 seconds. The robots are able to maintain a safe distance from the obstacles around them as well as the other robots. Upon arrival to the goal, the robots try to maintain the shortest distance from the goal, while aligning themselves with the already arrived robots.

An extra feature implemented is an on-board recording camera to reflect the driver's view from what the robot sees during its travel. This feature is currently used only for recording purposes, however it can be further extended later for control purposes. Multiple shots from the driver view camera are shown in figure 5.

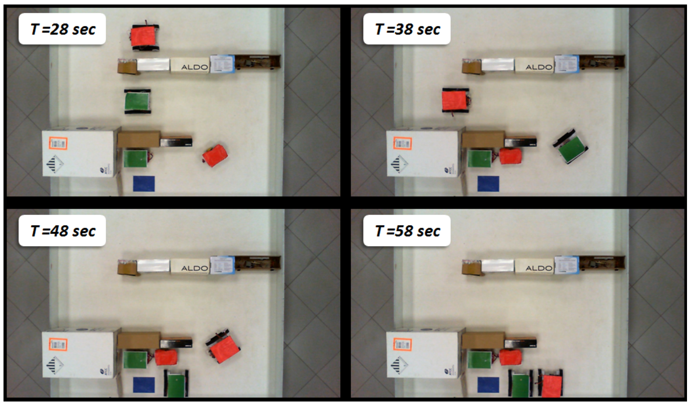

Fig. 4. Shots of the robots executing the scenario under study at different timings.

The trajectories of the robots are tracked using the overhead computer vision module for further plotting and analysis. The trajectory of the last arriving robot to the goal being the tracked vehicle number 2 is plotted in figure 6. This is the longest trajectory of all the robots, and as can be seen from the results, there exist an error between the expected ideal shortest path trajectory, and the actual trajectory that the robot followed based upon its own decisions and the readings it gets from the on-board sensors.
The evaluation metric previously defined is computed for each of the robots under study. The error between the ideal shortest trajectory and the actual trajectory followed by each of the robots is evaluated. Summary of the error of each of the robots is tabulated in table I.
From the results tabulated, it is clear that the robot with nearest initial condition (Wheeled Robot 1) to the goal, achieved the least error and vice versa. The values achieved reflect the fact that the path taken by the robots doesn't relate much to the ideal shortest distance trajectory, however it remain the most suitable trajectory considering the on-board controller and decision making process.

TABLE I. Evaluation Metric (Error) for all robots

Evaluation Metric	Wheeled Robot 1	Wheeled Robot 2	Tracked Vehicle 1	Tracked Vehicle 2
Error	8.32	11.6	13.73	18.59

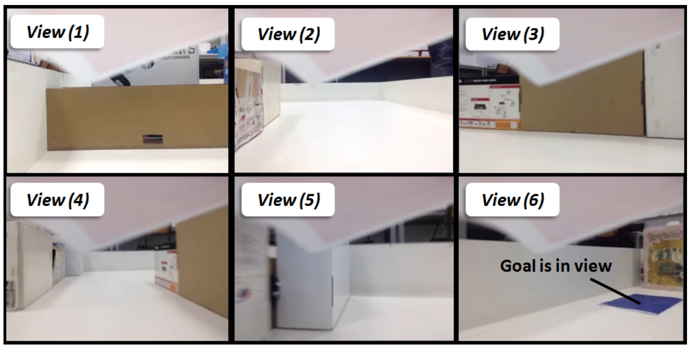

Fig. 5. Shots of the driver view from on-board camera

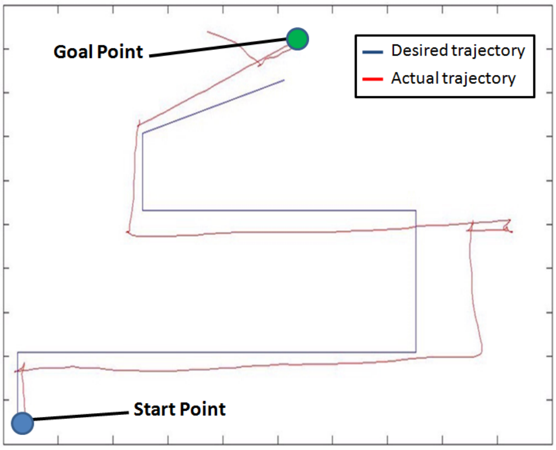

Fig. 6. Trajectories of the tracked vehicle robot 2

V. Conclusion and Future Work

In this study a low cost Multi-Robot System (MRS) experimental platform is developed and evaluated. The field of multi mobile robots research is a very active field of research that is widely studied by researchers to validate developed algorithms in various disciplines. Thus a robust experimental platform is required. However a compromise is always made between cost and quality of robotic platform used.

In this study, an approach to develop a robust experimental platform is proposed, through integrating a set of low cost commercially available components. Through a set of developed algorithms, the uncertainties in the sensors and the errors in the actuators are overcome. A group of four heterogeneous mobile robots are developed, controlled through a reliable short range radio frequency wireless communication channel. A test arena of size 2 meters in both length and width is built to test multiple scenarios. An overhead camera is fixed on top of the arena to provide visual feedback of the robots for the tracking algorithm.

Scenarios tested provided promising results for this developed platform, opening the door for more complex test scenarios, and further research problems to be investigated.

Further endeavors include studying different control architectures on the developed platform, such as centralized or hierarchical control architectures. Also the usage of on-board sensors can be considered in applications of interest such as the multi-robot Simultaneous Localization And Mapping (SLAM) problem.

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