Design of a Configurable All Terrain Mobile Robot Platform

Gokhan Bayar, A. Bugra Koku, E. ilhan Konukseven

***Abstract*—**With the increased funding from various agencies, research conducted in the field of mobile robotics has significantly increased during the last couple of decades. Due to wide range of applications mobile robots of different sizes and capabilities are required in the field. Despite the wide spectrum of applications to be developed for mobile robots, available platforms on the market for research purposes are very few in number, and limited in their capability for multi-purpose use. Evidently purchasing new platforms for different applications is not a feasible solution for conducting research. Driven by the motive of having a configurable research platform, a mobile robot referred to as CoMoRAT (Configurable Mobile Robot for All Terrain Applications) has been designed and manufactured at METU. CoMoRAT can be driven by wheels, tracks or both. Besides its ability to ride effectively on various terrains, robot body is designed in such a way that adding new hardware to the platform requires minimal manufacturing and installation effort. This paper presents the design and construction details as well as the performance tests conducted on CoMoRAT.

***Keywords*—**Mobile robot, design, construction, ground, platform, base, terrain, track, wheel.

I. INTRODUCTION

DEMAND for mobile robot applications has significantly increased in the past couple of decades and mobile robotics has become a rapidly developing field of interdisciplinary research within robotics. This promising field has attracted the attention of academicy, industry, as well as several government agencies. Currently from security to personal service, mobile robots are being used in a variety of tasks. Yet the use of such robots is expected to only increase in the near future.

The demand for consumer robots for various applications being on the rise [1], and the availability of various funds in addition to big stake competitions, both industry and academy have shown great interest in developing robotic hardware and applications. With the ultimate purpose of creating fully autonomous robots that can outsmart humans, wide range of applications for mobile platforms have been developed. Despite the rich spectrum of applications, mobile platforms available for research have been very few in number such as ATRV, Pioneer series robots [2, 5] and Packbot [7]. First of all these robots are not economically feasible, second, they are designed to operate on a specific environment, hence developing diverse applications that require installing additional hardware, and drive system manipulations cannot be easily and effectively done on these robots. Purchasing a new robot for every different application being developed is not feasible both in terms of money and time.

Different applications require the mobile robots to operate on different environments [14]. Some robots are designed to operate indoors, some outdoors, and some have to be able to operate in both. Robots operating outdoors may stay on the road or navigate off-road. For effective traversing diverse terrain, it is important to have a driving system that can easily be configured to suit the needs of navigation task at hand. Indoor environments are generally smooth and well structured, whereas outdoors, especially off-road sections, are rough and pose challenges for wheeled robots.

Various types of locomotion methods such as legs, wheels and tracks are used on mobile robots with various configurations. For instance, Plunstech walking robot, which has been designed for the forest applications, provides automatic leg coordination while the operator selects a travel direction [3]. Six-wheeled mobile robot, Sojourner, was designed for the mission of exploring Mars surface [4]. Both of these robots have excellent rough terrain navigation capability, yet they are neither available to researchers nor versatile for diverse applications. Pioneer mobile robot is one of the mobile robot bases that are commonly used in research [5].

Magellan mobile robot is another platform preferred by researchers. It is designed for indoor operation and commonly used in indoor navigation applications. Being decorated with various sensors, Magellan is not suitable for outdoor applications [6]. PackBot is a mobile robot platform used for the applications of explosive ordnance disposal, search-and-rescue, surveillance, bomb squad, swat teams, and other vital tasks [7].

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Table 1 Comparison chart about the features of the mobile robots (Adapted from [10])

	Sojourney	Magellan	Pioneer	Packbot	MR-5	Talon	CoMoRAT
Payload (kg)	4	9.1	22.7	25	80	150	15
Velocity (m/s)	2	2.5	1.6	1	1.5	2	1
Dimensions (mm)	225x400x 130	368 h:198	440x380x 220	525 h:1060	600x480x 465	1025x680x 440	300x500x 80
Motors	2x12V	2x24V	2x12V	4x24V	2x48V	2x48V	2x24V
Comp. Platform	Siemens	-	Siemens C166	Embedded PC	MPC555	MPC555	Embedded PC, Perip. Mic.
Development Tools	VB, C++ Matlab	C++	C++	C++	C	C	C# Matlab
Sensors and Equipments	I-U	O-I G-L	U-I-T LS-V GPS-C Gr-Pt	U-I-T LS-C-V GPS-Gr Pt	U-I-T LS-C-V GPS-Gr Pt	U-LS-C V-Gr-Pt	LS-G A-G-O
Communication	RS232 RF	RS232 Wireless RF	RS232 Wireless Ethernet	RS232 Wireless RF Ethernet	RS232 Wireless RF Ethernet	RS232 Wireless RF Ethernet	RS232 Wireless RF Bluetooth
Application	E	E	A,E,R	A,E,R	A,E,R	A,E,R	A,E,R
Actuation	W	W	W	T	W W+T	T	W,T W+T
Permission for Reconfiguration of Platform	No	No	No	Yes	Yes	Yes	Yes
Permission for Actuation Configuration	No	No	No	No	Yes	No	Yes

The annotations are: **E, A, R** are education, application, and research, respectively. **I, U, O, G** are infrared sensor, ultrasonic sensor, odometer, and gyro, respectively. **A, L, T, LS** are accelerometer, light captor, tactile sensor, and laser scanner, respectively. **V, Pt, C, GR** are vision system, pan tilt camera, navigation compass, and grippers, respectively

PackBot is a tough, light weight and quickly configurable platform. It also allows integrating flippers, a camera and a robotic arm on its frame. All the assembling and disassembling stages take only a short period of time and hence, it can be adapted to different situations very quickly. However, the price tag of this robot is quite a burden on a limited research budget.

MR-5 is a remotely controlled mobile robot base. It is ideally suited for explosive ordnance disposal, swat, harmful material search, surveillance and other hazardous environment and material tasks. It has been designed for operating with wheel and/or tracks [8]. It has two motion modes: wheels tracks on wheels. Being able to move on either wheels or tracks, MR-5 can be effectively operated in diverse environments and situations.

Another well-known mobile robot platform which is commonly used by U.S. military is Talon. It has been designed for the missions ranging from exploration of the working environments to weapons delivery [9]. Even though integrating some equipment to its base can be done very easily and quickly, its track based driving system cannot be modified. Besides its legendry success in military applications, Talon is not suitable for research and it is even more expensive than other platforms.

As a result, commercially available robots mentioned so far fall short in terms of being the ideal mid-size research platform. They are either not suitable for different terrain conditions, or they are not configurable enough to meet the needs of diverse research requirements. Evidently, purchasing a new robot for different research projects is not economically feasible in most cases. Hence, CoMoRAT is designed to be a modular, easy to reconfigure, on and off road capable mobile platform. CoMoRAT is compared to some well-known robots on the market in Table 1. Payload that robot can carry, velocity, dimensions, type of the motors that drive the robots, computational platform, development tools, sensors and equipments that can be attached, types of communication, application areas, and actuation types are compared in this table.

During research, developers often need to add and remove hardware when deploying new applications to a platform. Hence, physically adding new hardware (i.e. sensors, actuators, computational units) to the robotic platform should be practical. Diverse applications require the robot to move on various types of terrain. To increase the efficiency of the robot on different terrain, it is important if the robot can be configured to drive on wheels, tracks or both. CoMoRAT is designed with the expectations that traction system can be easily changed (to be wheeled, tracked and wheeled + tracked) to suit a wide range of terrain, and allow additional hardware to be installed with minimal manufacturing and effort. In terms of size, it is aimed to create a robot that can be backpacked by the user (end user, or the grad-student) if needed. This study does not attempt to individually address any specific robotic application, indeed it is aimed to shape up a robotic module that can be used in a wide range of applications on different terrain with proper modifications. It is tested with tracks, wheels, and with both tracks and wheels. The results are can potentially provide some guidelines and directions for other researches designing mobile robots.

In the remaining of the paper, the design requirements are presented in Section II followed by the brief introduction of the design process. Simulations and experiments in order to evaluate the performance of CoMoRAT are given in Section IV followed by the conclusions.

II. DESIGN REQUIREMENTS AND DECISIONS

A researcher has to deal with problems, the solution of which requires robots moving on various terrain conditions. Commonly used locomotion methods for mobile robots can be classified into there as legged, wheeled and tracked. Hybrid locomotion methods that fit a robot into more than one of these classes are also available in the literature. Legged locomotion provides perfect terrain adaptation hence increased mobility on diverse terrain conditions for mobile robots. Yet, this kind of locomotion is mechanically complex, which in turn brings the disadvantage of slower motion and decreased system reliability. Wheeled and tracked locomotion offers faster and more reliable solutions, yet they lack the adaptation capability of legged locomotion. Wheeled robots can move and maneuver rapidly on structured roads effectively where tracked robots have relatively better performance when the robot moves off the road, traverse over steep hills. In conclusion choosing one of these three methods to mobilize a robot introduces a trade-off that has to be faced by a researcher.

Indeed the real trade-off that robotic researchers frequently face is when a robot has to be purchased. It is evident that a researcher has to deal with different applications in time, yet most of the commercially available robots on the market do not provide a generic solution to suit the needs of a diversified robotics researcher. Such a researcher has to deal with robots moving on different environments (indoor, structure and unstructured terrain etc.). Based on the applications various types of hardware have to be installed on the development platform. As a result, a robotic researcher often feels the need for a mobile platform; that can effectively move on different terrain conditions and to which addition of new hardware is practical. Since purchasing a new robot for every different application is neither economically nor time-wise practical. Hence, we have felt the need to develop a single, yet easily re-configurable mobile platform at the Department of Mechanical Engineering at METU which can be used wide range of applications with minimal effort.

At the beginning of this study, the design requirements of CoMoRAT are determined as follows:

- Selection of one of the three locomotion method is going to restrict the effectiveness of the designed robot. Locomotion is to be selected in such a way that a wide range of applications should be deployable to the developed platform.
- Diverse applications require different hardware to be present on a robot. Hence, the robot body should enable addition and relocation of hardware.
- Addition of new hardware to the robot should require minimal manufacturing and installation should not be cumbersome.
- If possible a standard mechanical interface should be determined and any hardware following this interface should be easily mounted on the mobile platform.
- Any reconfiguration work on the robot should be practical, consume minimal time and not require personal talent.
- The robot should easily be adopted by different students with different programming backgrounds in order to increase the usability of the platform.

With these requirements in mind, CoMoRAT design process is initiated. Due to its mechanical and control complexity, relatively slow motion, low reliability and possibility of high maintenance requirements legged locomotion is opted out. Between wheeled and tracked locomotion, neither one is preferred to the other basically due to the fact that, wheeled robots perform better on structured roads whereas tracked robots outperform wheeled ones when the terrain is unstructured and especially when the surface is very rough and steep hills is to be traversed. However, it is also possible that during operation a robot will not stay in one type of terrain at all times. In such cases, bringing the best of two worlds together will increase the effectiveness of the robot, hence, it is decided that the robot locomotion should enable it to be configured as wheeled, tracked or wheeled + tracked at the same time.

Necessity to add different hardware to a robot is frequently faced by robotics researchers. Especially, research on limited budget demands such multi-purpose use. To highlight this fact consider two grad students working on different projects. They may end up using the same robot base but different hardware has to be installed on them so that they can conduct their own research. In many such cases purchasing a new robot for each and every student in a research lab is not possible; hence, these robots should enable hardware re-configurability as much as possible.

Many of the commercially available robots do not provide a practical solution to this hardware re-configurability need. Robot bodies should be drilled when an installed hardware is removed; most of the installation holes remain on the robot body. This is not only cosmetically a flaw; it also is a treat to the sealed inner content of the robot. As shown in Figure 1, the robot body frame is constructed from extruded aluminum with groves on both side of the frame. This frame structure enables us to design simple adaptor plates for individual hardware components and locate the hardware either inside or outside the robot with the same adapter. It is also very practical to move the hardware once it is installed on a groove to open up some space for additional hardware. Another advantage of the grooved frame structure is that, by moving the hardware (including the batteries) within and around the robot, the center of gravity of the robot can be adjusted as needed.

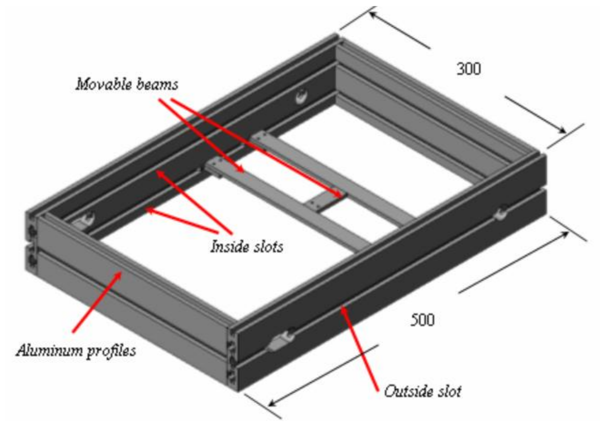

Fig. 1 Frame of the robot base

Finally, although configurable locomotion and hardware are necessary conditions for a multi-purpose mobile research platform, hardware integration to the overall control system is an issue that has to be handled via software. Hence, the base should not restrict the user to a specific operating system. Considering the fact that, bare bone CoMoRAT contains only the driving system, the basic need is portable motor control software. At this point, Maxon motors and EPOS controllers provide an easy yet affordable and reliable solution. CoMoRAT's Maxon motors can easily be controlled via RS232 which enables the user command the base through any device that implements a not-so-complicated serial protocol.

III. DESIGN PROCEDURE

In order to select CoMoRAT's actuators, a simple model of the platform as illustrated in Figure 2 is derived. Note that the model has been developed for an ideal flat surface condition in order to have an idea about the general requirements of the motion. In the mathematical model the forces coming from ground has been taken into account. The applied wheels' traction forces, which are needed to give the motion to the robot base, have been modeled as given in Equations (1-6). The abbreviations used in Figure 2 are specified as: m denotes the mass of the platform. g denotes the gravitational acceleration. h_{mg} denotes height of the center of mass. F_{Nr} and F_{Nf} denote the normal forces acting on rear and front wheel, respectively. F_{Tr} and F_{Tf} denote the total tractive effort for rear and front wheel, respectively. γ_f and γ_r equal 1 for the four wheel drive. θ is the slope angle of the terrain. The details of the model are given in [11].

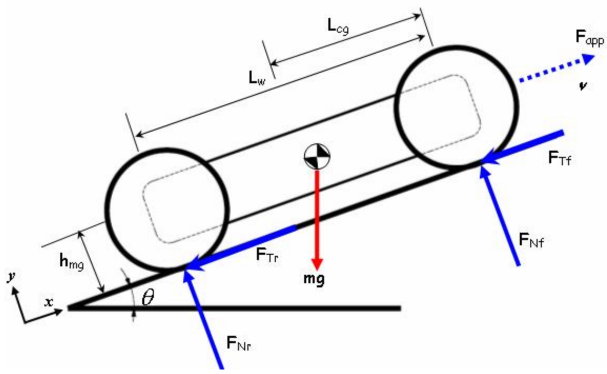

Fig. 2 Motion model of the mobile robot platform

$$\sum F_x = \mu_w \gamma_r F_{Nr} + \mu_w \gamma_f F_{Nf} - mg \sin\theta \tag{1}$$

$$\sum F_y = F_{Nr} + F_{Nf} - mg \cos\theta \tag{2}$$

$$\sum M = F_{Nr} L_w - mg(L_{cg} \cos\theta + h \sin\theta) \tag{3}$$

$$F_{Nr} = \frac{mg(L_{cg} \cos\theta + h \sin\theta)}{L_w} \tag{4}$$

$$F_{Nf} = \frac{mg((L_w - L_{cg}) \cos\theta - h \sin\theta)}{L_w} \tag{5}$$

$$F_{app} = F_{Nr}\,\mu + F_{Nf}\,\mu + mg\sin\theta \qquad (6)$$

CAD models of the wheeled, tracked and wheeled + tracked versions of CoMoRAT are given in Figures 3-4-5, respectively. The mathematical model of the mobile robot platform has been simulated in Matlab. In the design process, SolidWorks is used. The dimensions of the parts have been optimized using the CosmosWorks finite element analysis (FEA) software.

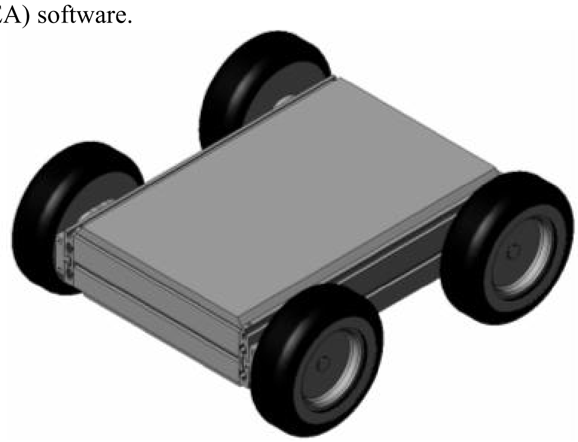

Fig. 3 CAD model of wheeled model of CoMoRAT

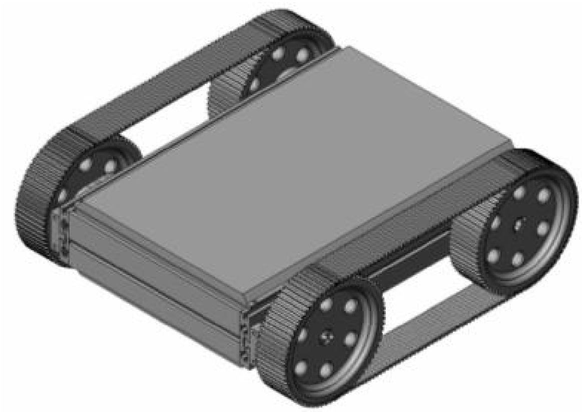

Fig. 4 CAD model of tracked model of CoMoRAT

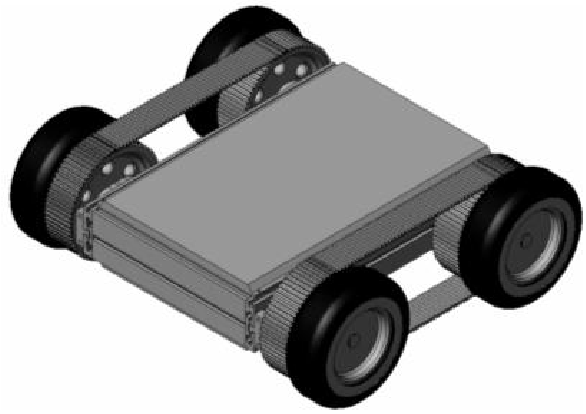

Fig. 5 CAD model of wheeled + tracked model of CoMoRAT

In the strength analysis of the components, it is aimed that the profiles of the frames should be reliable under the load corresponding to a weight of 70 kg man. Frame of the mobile robot has been manufactured from 6061 series of Aluminum profiles. Two sliding slots have been manufactured inside the profile. As shown in Figure 1, the beams, which are fastened to the sliding slots, can be easily moved. By this way, internal space of the platform can be rearranged and used effectively whenever it is required. Linear sliding slots are designed at the outside of the base profile. In order to connect the motor mounting to the frame and to adjust the tightness of the pallets, these slots can be used. Moreover, using these slots, the driving type can be rapidly configured within a few minutes.

Fig. 6 Exploded view of the robot's configurable driving systems

Wheels and pulley wheels have been connected to the frame by two shafts. Dimensions of the shafts, shaft hole of the wheels and pulley wheels have been designed in a way that they get along well with each other. In other words, inner and outer shafts can be used for wheels or pulley wheels. The stages of the assembly are given in Figure 6 where the two shafts are joined with a set screw and the shafts are connected with wheels and pulley wheels by keys.

Fig. 7 Manufactured reconfigurable mobile platform

Figure 7 shows the manufactured wheeled + tracked version of the mobile robot. Tracked and wheeled versions are given in Figure 8 and 9, respectively. The physical parameters of the mobile robot shown in Figure 2 and 10 are $D_{rw} = D_{fw} =$ 200 mm, $L_w = 347$ mm, $L_{cg} = 173.5$ mm, $h = h_{mg} = 100$ mm, $\mu_w = 0.5$, $\gamma_f = \gamma_r = 1$. DC motors which drive the mobile platform have an operating voltage range of 12 to 24 V, maximum speed of 72 rpm (0.35 A) at no load and speed of 36 rpm with 54.6 kg.cm torque at maximum efficiency. The motors give 40 Watt output power at maximum efficiency. They draw 6 A current and produce 240 kg.cm torque at stall. The details of the model and the design parameters are given in [11].

Fig. 8 Tracked mobile robot

Fig. 9 Wheeled mobile robot

As mentioned in this section, the mobile robot platform has been designed for flat, rough and uneven terrain applications. Three driving systems have been merged into one platform. By this way mobile robot can be used for different applications with proper configuration.

IV. EXPERIMENTS CONDUCTED WITH CoMoRAT

CoMoRAT gives the opportunity for various applications performed in both indoor and outdoor environments. In order to show the usability of the platform, some experiments have been conducted and the results are presented in this section. These experiments are slope climbing, obstacle crossing over and power consumption. Moreover, tip over angles for the up and side motions have been obtained during the slope experiments. All the experiment outcomes have been compared with the simulation results.

A. Slope Climbing

Mobile platform with its three configurations has been tested in the mixed terrain that is composed of small size gravel and worn concrete. The surface on which experiments have been conducted has also inclination. Experiment and simulation results have been figured out in Table 2 in order to make a comparison. Tipping over angles (up and side motion) of the configurations has been also obtained during those experiments. Wheeled configuration has been failed for climbing more than 19^0 of slope angle. The mobile platform with wheeled + tracked configuration has climbed through 28^0 of slope angle. This result gives a nearby result that has been obtained by the only tracked version. Hence a brief conclusion can be made for this experiment that wheeled configuration can be more powerful if it is combined with tracks. Wheeled + tracked version of the mobile platform has designated an advantage that it is more successful for climbing a slope than wheeled one. As a result of this test it, can be concluded that tracked or tracked + wheeled mobile robots can be surely used in an environment having the features of mixed terrain and slope, rather than using wheeled robot.

Table 2**.** Experimental and simulation results for observing capability of slope climbing in degrees (T denotes tracked and W denotes wheeled mobile platform)

	Exp.	Sim.	Tip Over Angle (Up)	Tip Over Angle (Side)
T	31	34	60	70
W	19	20	60	70
T+W	28	31	62	72

Mobile platform with its three configurations has been tested for velocity analysis. In order to show the performance of the configurations, no load speed of the mobile platform has been set to 1 m/s. Then, they have been tested on an indoor flat surface and on an outdoor surface composed of small size gravel and worn concrete. Configurations have been tested for a short path. While the mobile platform is traversing the path, the average velocity is obtained. The experimental results given in Table 3 show that the velocity of the tracked version of the mobile platform can be increased by adding wheels.

Table 3. Velocity (m/s) of different mobile platform configurations

	Wheeled	Tracked	Tracked + Wheeled
Indoor	0.8	0.6	0.7
Outdoor	0.7	0.5	0.6

B. Crossing Over an Obstacle

In order to analyze obstacle crossing over capabilities of CoMoRAT, a mathematical model is derived and a scenario is considered. In this scenario, robot makes an effort to cross over an obstacle that is placed just in front of it (Figure 10). Images from the experiments are also given in Figure 11.

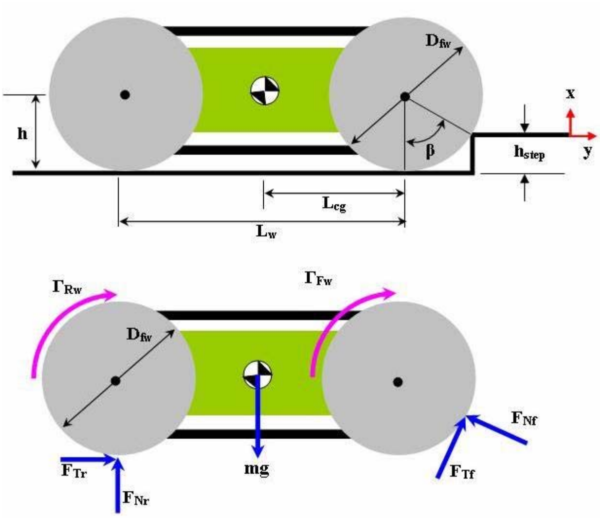

Fig. 10 Motion model of the mobile robot platform for crossing over an obstacle

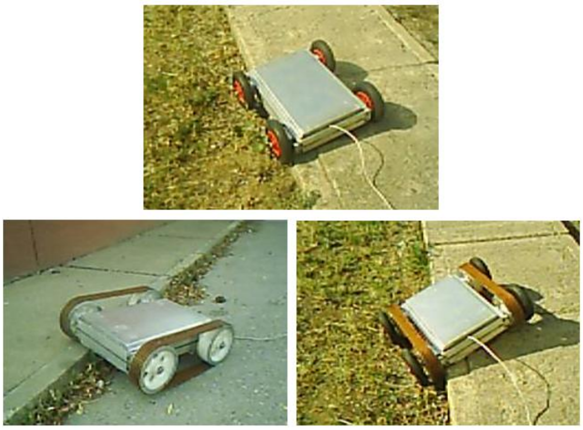
Fig. 11 Crossing over a step

Normal forces and total tractive efforts required for crossing over an obstacle obtained from the contact points between wheel(s) and obstacle are specified in Figure 10. D_{rw} and D_{fw} denote the rear and front wheel diameter, respectively. μ denotes the coefficient of friction between the wheel/track and obstacle. h denotes the height of center of mass about plane. h_{step} denotes the height of the obstacle. Γ_{Rw} and Γ_{Fw} indicate the required torques for rear and front wheel, respectively. β indicates the contact angle between the wheel/track and the obstacle. Normal and tractive forces are obtained for one wheel and two wheel blocked with an obstacle. Normal forces for the rear and front wheels in case of two wheel contact are given in Equation (7-8).The details of the mathematical model can be found in [11]. Note that the shape of the obstacles used in these experiments is rectangular.

$$F_{Nr} = \frac{2mg(L_{cg} + R\sin\beta)}{L_w + (D_{fw}/2)\sin\beta} \tag{7}$$

$$F_{Nf} = \frac{2mgL_w - L_{cg}}{(L_w + (D_{fw}/2)\sin\beta)(\cos\beta + \mu\gamma_f \sin\beta)} \tag{8}$$

CoMoRAT's different configurations have been tested with various obstacles having different heights. The experiment results are given in Table 4 (+ and - signs indicate successful and unsuccessful results about crossing over an obstacle respectively). Note that radiuses of the wheels and pulley wheels of the robot platform are 10 cm and 9 cm, respectively. Tracked configuration of the robot platform has been successful for the five different obstacles that heights are ranging from 6.4 cm to 13 cm. Tracked + wheeled configuration has managed to cross over all the obstacles except the last one having 13 cm height. Tracked and tracked + wheeled configurations of the platform give acceptable results. However, wheeled configuration is successful for only two obstacles having heights of 6.4 cm and 8 cm. From these experiments, tracked and tracked + wheeled versions have shown their dominancy about crossing over an obstacle.

Table **4.** Experiment results for crossing over obstacles

Height of Obstacle (cm)	6.4	8	9	11	13
Tracked	+	+	+	+	+
Wheeled	+	+	-	-	-
Tracked + Wheeled	+	+	+	+	-

For the obstacle crossing over experiments, CoMoRAT has been tested with the obstacles in two cases. In the first case, one wheel of the platform has blocked with the obstacle. In the second case two wheels have blocked with the obstacle. Experiment and simulation results are given in Table 5.

Table 5. Experimental and simulation results for crossing over obstacle

	One Wheel Contact		Two Wheel Contact	
	Analytical Results (cm)	Exp. Results (cm)	Analytical Results (cm)	Exp. Results (cm)
T	9	8	7	6.4
W	18	13	11	9
T+ W	14	11	9.5	7

C. Power Consumption

Three different configurations of CoMoRAT have been tested in indoor and outdoor environments for measuring the current drawn for a certain traversed distance. During tests the voltage of the motors is set to 24V and three different configurations have been tested for 10 m long straight path. The indoor test area is smooth flat surface. On the other hand, surface of the outdoor test area is composed of small size gravel and worn concrete. The results are listed in Table 6.

Table 6. Power consumption experiments

		Current drawn during motion (A)	Time traveled (s)
Tracked	Indoor	1.1-1.3	16.6
	Outdoor	1.4-2.2	20
Wheeled	Indoor	0.9-1.1	12.5
	Outdoor	1.1-1.5	14.5
Tracked + Wheeled	Indoor	1.3-1.4	14.7
	Outdoor	1.5-2.5	17

Power consumptions of three configurations can be evaluated using Table 6. Results indicate that wheeled configuration draws the lowest current and it has the highest speed.

V. Conclusion

While developing diverse applications for mobile robots, a researcher inevitably feels the need for a configurable robot that can efficiently operate both indoors and outdoors, onto which various hardware can easily be installed and removed. CoMoRAT is developed with this perspective, to be a small size mobile robot suitable for academic research running on a limited budget. The traction system can be configured to use wheels, tracks or both. Body of the robot provides a closure for batteries, motor drivers and main computer. Additional hardware can easily be installed both inside and outside of the robot. Main frame is constructed from Aluminum profile which has groves to facilitate addition of hardware easily. Field tests conducted on the robot are in agreement with the simulations run prior to manufacturing the robot. As a result, a configurable robot platform is designed, manufactured and tested and CoMoRAT proved to meet the expectations as a versatile mobile robot platform to be used in academic research.

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