

# Improved Design of a Wheeled Hybrid Mobile Robot, Modeling and Co-Simulation

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## Abstract

This paper presents a new design of a Wheeled Hybrid Mobile Robot, in order to increase the maneuvering and obstacles crossing abilities in normal operation case and to decrease cost and complexity of the mechanical design. These new design possibilities come from building a virtual prototype in ADAMS® to carry out the dynamic performance analysis of the robot. This modelling identifies motor moments for the implementation of each mission. Interactive ADAMS®/MATLAB SIMULINK® co-simulation could help designers considering simultaneously the two primary parts of mechanics and control, which permits to improve and develop the engineering design before proceeding to manufacturing, and consequently results in higher efficiency and saves time and money.

**Keywords:** robot, hybrid, co-simulation, wheeled, dynamic. ADAMS®

## INTRODUCTION

Mobile robots have been used to perform dangerous or tedious tasks for human, searching for victims through the rubble and in the detection of hazardous materials. Nowadays the available technology is more efficient and less costly.

Increasingly mobile robotic platforms are being proposed for high-risk missions in military applications like MDARS [1], hazardous site clean-up like KNIGHT A [2], and planetary explorations [3, 4]. These missions require mobile robots to perform complex locomotion and manipulation, and self-righting when it falls or flips over. The new designs have significantly improved the ability to move in rough terrain with various obstacles. Continuously efforts are made in designing robots that allow a wider control over centre of gravity location [5] in order to increase robustness to effects of terrain roughness. However, the application of these solutions leads to complex design that makes the robot-driving task very difficult. In addition, it increases the manufacturing cost.

In our study, we redesign the Tracked Hybrid Mobile Robot [6] in the form of a Wheeled Hybrid Mobile Robot. Wheeled Hybrid Mobile Robot is similar to the Tracked Hybrid Mobile Robot in terms of dimensions, weight and design of some mechanical parts.

Focusing on the movement of the wheeled robot from a holistic kinetic configuration, good locomotion capability is the key characteristic of field robots working on uneven

outdoor terrain. They should be able to operate on sand, snow, swamp or even over rocky terrain. Therefore, the construction of such robots is different from the traditional ways of building robots, The robot needs a reliable control tools to operate without human intervention to sense the environment and control the movement in real time, and it leads to the need to build an integrated system, and taking into account all of the following components:

1-Power and energy system. 2-Motion and action planning system. 3-Motion control system. 4-Navigation system. 5-perception system. 6-Man-machine interface and remote control system. 7-Working tool systems.

In addition, the use of ADAMS®/MATLAB SIMULINK® co-simulation for robot design is more efficient to show the robot's abilities to respond to commands and perform required movements [7].

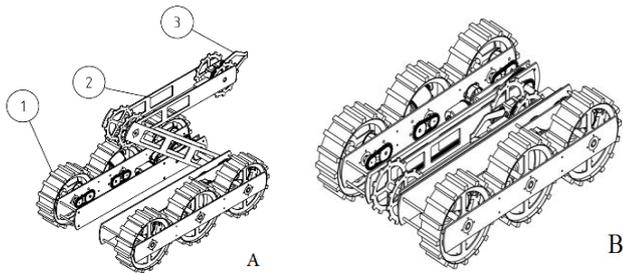
This paper is organised as follows: Mechanical design is developed in section 2. In section 3, sequential steps for obstacles crossing are presented. In section 4, result of performed simulation in MSC ADAMS®. Modeling of control system is discussed in section 5. In section 6, the procedure of building the co-simulation is presented.

## MECHANICAL DESIGN

### A. Mechanical Design Architecture

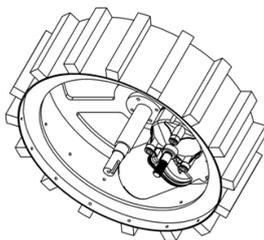
The proposed design is a systematic and practical one; it deals with the robotic system overall operation. Mechanical structure, is designed using CATIA® software, is characterized by The following points:

- The manipulator arm and the mobile platform are designed and packaged, as one entity rather than two separate modules. The mobile platform is a part of the manipulator arm, and the arm is a part of the platform. This hybrid approach may result in a simpler but more robust design, significant weight reduction, higher end-effector payload capability and lower production cost.
- The design architecture with the arm integrated in the platform eliminates the exposure to the surroundings, when the arms is folded during motion of the mobile platform toward a target. As soon as the target is reached, the arm is deployed in order to execute desired tasks (Fig.1.)



**Figure 1:** Mechanical Design Architecture: A: open configuration, B: closed configuration

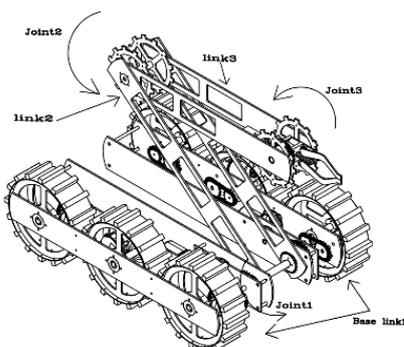
- The platform is fully symmetric even with the integrated manipulator arm, thus it keeps moving toward the target from any situation with no need of additional active means for self-righting when it falls or flips over.
- The robot is able to overcome obstacles to reach a height of up to 15 cm without need to use the arm.
- It Takes advantage of the space available inside the wheels to put the wheels motors (Fig.2), and saves more space within the body of the robot.



**Figure 2:** Motor inside the wheel

The robot consists of three main sub-systems (Fig.3):

1. **The platform:** It consists of two identical mirrored parts, right part and left part, each one consisting of three wheels, the body that contains the electronic components, and the arms moving mechanisms. These two parts are linked with the rotational axis of the joint 1.



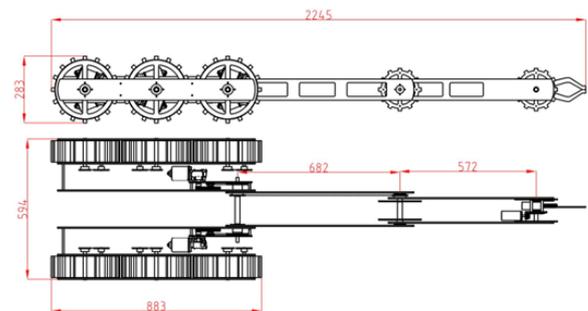
**Figure 3:** Key links of the robot

2. **The arm:** It is a two-part linked by rotational joint 2; the first part is linked to the platform with a rotational joint 1. The second part ends with a rotational joint 3 with the grip. It is provided with passive wheels on pivot joints 2 and 3, which helps the robot to move when relying on the arm.

3. **The grip:** It comprises the mechanism to rotate the grip around the axis of rotation, and a mechanism to open and close the jaws of the grip.

*B. Design specifications of the robot*

The total weight of the robot is 65 kg, the maximum velocity is about 1m/s. Fig.4 shows the dimensional of the robot.



**Figure 4:** The dimensional design of the robot

*C. Mechanical systemModelling*

The 3D mechanical design assembly is developed with CATIA® software, and is exported to MSC ADAMS® to analyse the mechanical design to perform motion simulations to study the robot's enhanced mobility characteristics through animations of different possible tasks that require various locomotion and manipulation capabilities [6]. Then, an ADAMS®-based mechanical system model can be obtained, using the following procedure:

1. Setting parameters: such as the gravitational acceleration, material properties, etc.
2. Adding constraints, driving moments and loading. Through constraints, the components are associated with each other and the relative motion is limited [8].
3. For each task, finding the sequence of movements necessary to complete the task.
4. Determine the torque required to implement the motion with the fixed speed angle, and determine the transfer gears and chains ratios.
5. Creation of state variables in model ADAMS® and export state variables of dynamic model to MATLAB®, where the state variables are the key links of the internal information inflow and outflow in the ADAMS® model.
6. Establishing interfaces: The principle connection of the co-simulation is the digital signals, which are produced in one step in ADAMS® and SIMULINK®, are

respectively transferred through interfaces. This process continues until the simulation ends [9].

7. Simulation modelling of virtual prototype. The control scheme in SIMULINK® uses The ADAMS® model.

D. ADAMS® –Based Mechanical System Modelling and the results

By following the steps described in the last section, we get in ADAMS® a virtual prototype (Fig.5)

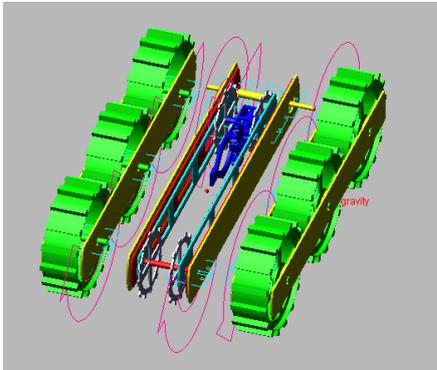


Figure 5: The virtual prototype.

CROSSING OBSTACLES

The study will address a range of key cases associated with the high barrier or type robot that show the possibilities of these cases are:

A. High obstacles less than 16 cm

They represent work in the natural state of the robot without having to use the arm to overcome obstacles, and the study will work on flat ground with obstacles in the form of the degree of heights ranging between 10 cm and 18 cm using MSC ADAMS® we get the moments of the required motors (Figure 7).

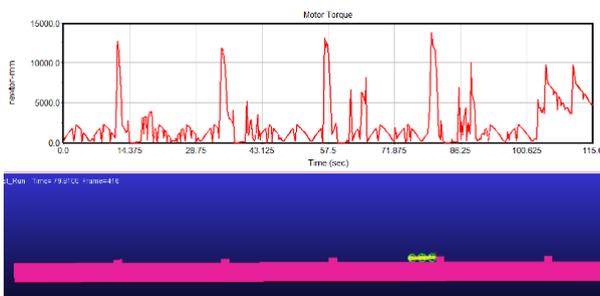


Figure 6: The obstacle height is less than 16 cm.

The robot was able to overcome obstacles up to 16 cm while failing to overcome the obstacle height of 18 cm. The maximum torque required by the motor to overtake the upper obstacle (16 cm) is 13.8 Nm (Fig. 7).

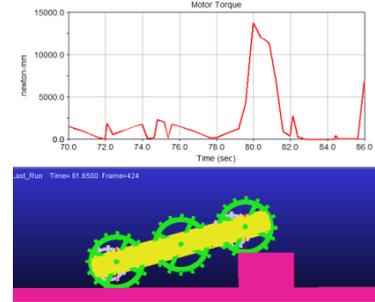


Figure 7: The obstacle height is less than 16cm.

B. The height of the obstacle is less than 25 cm

Fig.8 shows a simulation of the climb on a 25cm high step obstacle, and shows the sequence of steps necessary to achieve this:

1. Approaching the obstacle to a predetermined distance.
2. Rotate the joint 1 until the first arm rests on the obstacle.
3. Continue to rotate the joint 1 until the robot is based on the rear wheels of the base and the center of the second wheel becomes higher than the obstacle.
4. The base is moving forward until the second wheel is based on the obstacle.
- 5 - Continue to advance the base forward with the fold of the arm within the base.

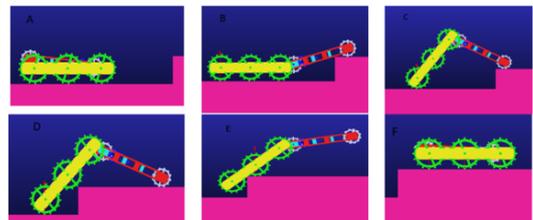


Figure 8: The obstacle height is less than 25cm

The maximum torque to be applied to the base wheels is 15Nm (Fig.9), and the maximum torque to be applied to the axis of the first arm is 93Nm (Fig. 10).

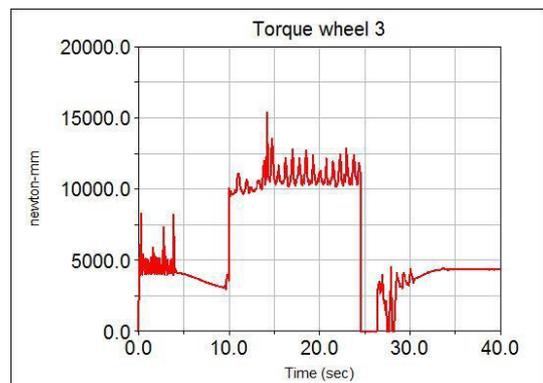
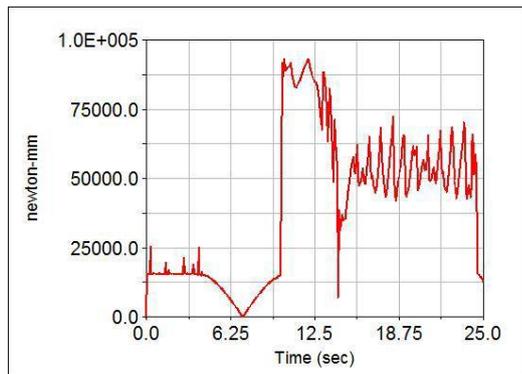
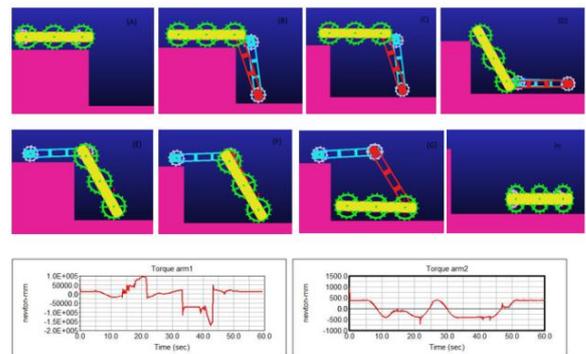


Figure 9: The torque requirement at wheels



**Figure 10:** The torque requirement at joint1



**Figure 12:** Step obstacle descending.

*C. General situation of overcoming obstacles*

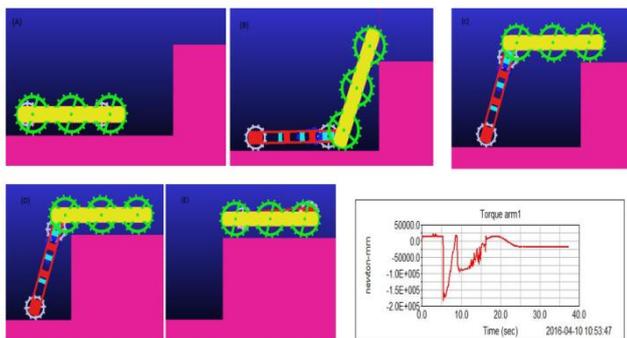
There are several types of obstacles, crossing them will be studied with determining the torque required in each case [10].

*1) Step obstacle climbing*

Fig.11 shows series of steps sequence in order to climb 0.7 m step obstacle, the steps are as follows:

- 1- Approaching the obstacle to a predefined distance.
- 2- The base link is first deployed on the step.
- 3-Link 2 continues to rotate until the base link is adjusted with the profile of the terrain.
- 4- The base progresses forward until all the wheels become on the obstacle.
- 5-Link 2 closes.

The maximum torque requirement at joint 1 is 170 Nm.



**Figure 11:** Step obstacle climbing.

*2) Step obstacle descending*

Fig.12 shows series of steps in order to descend step obstacle, height of 70cm, and the steps are as follows:

- 1- Approaching the obstacle to a predefined distance.
- 2-Link 2 rotates until the wheels at the end of the first arm rests on the ground.
- 3- The robot advances, until it is based only on the rear wheels.
- 4-Link 2 rotates to lower the front of the platform.
- 5-Link 2 closes and Link 3 opens to support the robot when moving forward.
- 6-Link 2 rotates until the wheels fully contact the ground.
- 7- Link 2 and 3 closes.

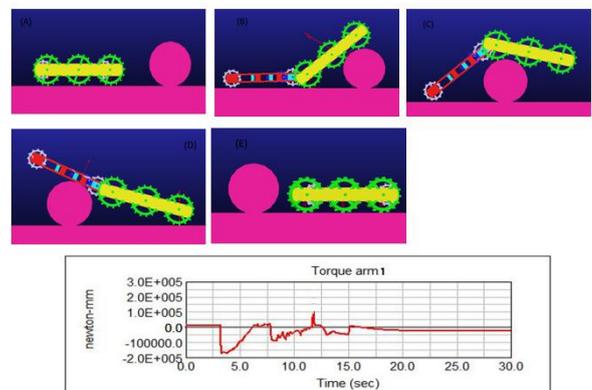
The maximum torque requirement at joint 1 is 170 Nm.

*3) Surmounting cylindrical obstacles*

Fig.13 shows series of steps in order to surmount cylindrical obstacle, 40cm in diameter, and the steps are as follows:

- 1- Approaching the obstacle to a predefined distance.
- 2-The base link is deployed until it touches the obstacle.
- 3-At that point, the wheels propel the platform.
- 4- At the same time they continue to rotate about joint 1.
- 5- The base progresses forward.
- 6- Link 2 closes.

The maximum torque requirement at joint 1 is 170 Nm.



**Figure 13:** Surmounting cylindrical obstacles.

*4) Ditch crossing*

Fig.14 shows series of motion steps in order to cross a ditch obstacle, with a maximum width of 0.7 m, and the steps are as follows:

- 1- Approaching the edge of the obstacle to a predetermined distance.
- 2- The link 2 is deployed until touching the ground on the other side of the ditch.
- 3- The base progresses forward until the front and back wheels are supported by the ditch edges.
- 4-Link 2 closes and the link 3 is deployed from the back until it touches the ground.
- 5-The base progresses forward until the back wheels passes the front edge of the ditch.
- 6- Link 3 closes.

The maximum torque requirement at joint 1 is 170 Nm and at joint 2 is 120Nm.

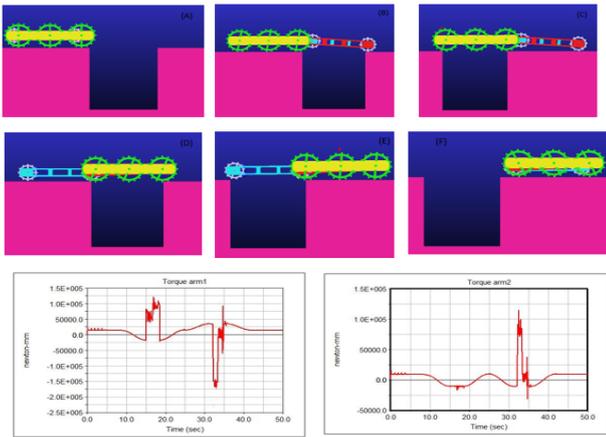


Figure 14: Ditch crossing.

5) Stair ascending

Fig.15 shows series of motions in order to ascend stair, and the steps are as follows:

- 1- Approaching the edge of the obstacle to a predetermined distance the base link is deployed until it touches the stairs.
- 2- Link 2 closes
- 3- The robot advances until the entire platform is on the stairs.
- 5- The platform ascend the stairs.

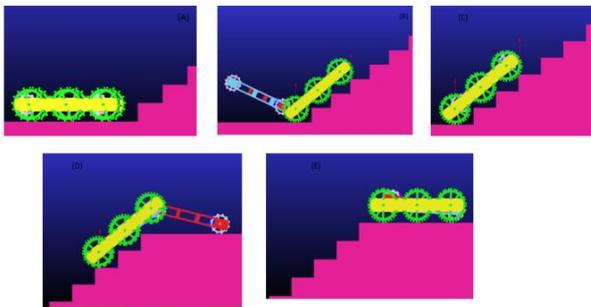


Figure 15: Stair ascending.

PERFORMED SIMULATIONS IN MSC ADAMS®

In order to establish the motion of the mobile robot, it is necessary: the motors joints 1, 2 provide a torque equal 15Nm for the angular velocity 0.52rad/sec, the motor platform provides a torque equal to 11Nm when the linear speed 1 m/sec for the coefficient of friction of 0.3 and the slope angle of 30°. These values was obtained from the simulations performed in MSC ADAMS®, and for this purpose, it was chosen the highest value obtained from the simulations. The parameters of the commercial motors Windshield Wiper Motors /Sorel selected are shown in Table 1.

Table 1: Motor Parameters

RPM	$K_b$ V/rad	$K_t$ Nm/A	R Ω	L mH	T Nm	Vin V	Gear ratio
2627	0.06	0.06	1.5	0.45	21	24	1/50

THE CONTROL SYSTEM MODELLING

The mobile robot motion control is simplified to a motor velocity control (Fig.16) [11]. The motor is an electromechanical system with electrical and mechanical components; the equations of motion for the robot will consider the simple case of single-degree-of-freedom motion of the robot, moving forward and backward. A simplified model of a symmetric one wheel of the robot is constructed as shown in Fig.17.

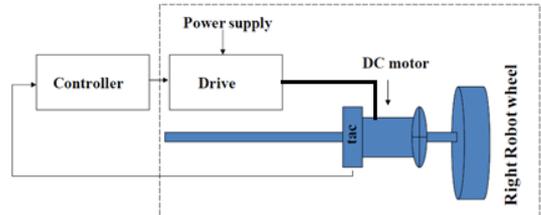


Figure 16: A simple model of one wheel

The following velocity transfer function is:

$$G_m = \frac{\omega(s)}{E(s)} = \frac{K_t}{[(Ls + R_a)(J_ms + B_m) + K_t K_b]} \quad (5)$$

Where

$R_a$ =armature resistance.

L = armature winding inductance.

$B_m$ = the viscous friction.

$K_t$ = the torque constant.

$K_b$ = back emf constant.

A. Differential Drive Kinematics

The rotation of the robot is realised by differential drive. By neglecting the effect of wheels sliding can be considered the speed of the wheels on each side of the robot being equal, in order to write linear speed ( $V_{robot}$ ) and angular velocity ( $\omega_{robot}$ ) of the robot base center of gravity in terms of linear speed of the left wheels ( $V_L$ ) and right wheels ( $V_r$ ) as follows [11]:

$$V_{robot} = \frac{V_r + V_L}{2}$$

$$\omega_{robot} = \frac{V_r - V_L}{B}$$

Where B is the distance between the robot's wheels. The radius of rotation R is calculated by the following formula:

$$R = \frac{V_{robot}}{\omega_{robot}} = \frac{B V_r + V_L}{2 V_r - V_L}$$

The kinematic model is given by:

$$\dot{x} = \frac{r}{2} (V_r + V_L) \cos\theta$$

$$\dot{y} = \frac{r}{2}(V_r + V_L)\sin\theta$$

$$\dot{\theta} = \frac{r}{B}(V_r - V_L)$$

Thus, angular velocity of the left wheels ( $\omega_L$ ) and right wheels ( $\omega_r$ ) can be written in terms of linear speed and angular velocity of the robot as follows:

$$\omega_r = \frac{2V_{robot} + B\omega_{robot}}{2r}$$

$$\omega_L = \frac{2V_{robot} - B\omega_{robot}}{2r}$$

Where r is the radius of the wheels of the robot.

There are three interesting cases with these kinds of drives.

1. If  $V_r = V_L$ , then this is the case of forward linear motion in a straight line. R becomes infinite, and there is effectively no rotation, and  $\omega$  is zero.
2. If  $V_r = -V_L$ , then  $R = 0$ , this is the case of rotation about the midpoint of the wheel axis.
3. If  $V_L = 0$ , this is the case of rotation about the left wheel. In this case  $R = B$ . Same it is true if  $V_r = 0$ .

### B. PI controller design

PI controllers will be used to get the desired response from the robot. The mechanical design of the robot is complex, making the process of finding a model for the dynamic model of the robot difficult, in addition to the existence of several dynamic models for this type of robot, therefore, the PI parameters will be determined using the co-simulation.

## CO-SIMULATION MODEL OF WHEELED HYBRID MOBILE ROBOT

Wheeled hybrid mobile robot is a complex electromechanical system. There are many motors and it exhibits complicated coupling relationships and nonlinear features.

In traditional design method, mechanical system design is separated from control system design without recognizing any coupling relationships between them. Using this method, it is not only difficult to improve mechanical properties of robot, but it can consume plenty of fund and manpower resources [8].

A better alternative is to use Co-simulation ADAMS®/MATLAB-SIMULINK®, which consists of two parts modelling of mechanical system and control system, then make a link between them in order to create virtual prototype and proceed to verification and testing before manufacturing (Fig.17) [14].

### A. Building the interface between ADAMS® and MATLAB-SIMULINK®

The model built in ADAMS®, as a sub-system; need to be imported into MATLAB/SIMULINK®, where SIMULINK® constructs the co-simulation system. First step is to exchange data between ADAMS® and MATLAB/SIMULINK® through ADAMS®/CONTROL interface (Fig.18). Second, define 15 system variables which are needed in co-simulation, there are 5 inputs systems variables: the angular velocity of the motors, and ten output variables: the angular velocity of the motors, the position of the platform centre of gravity and the rotation angels of the arms and the grip (Fig.19).

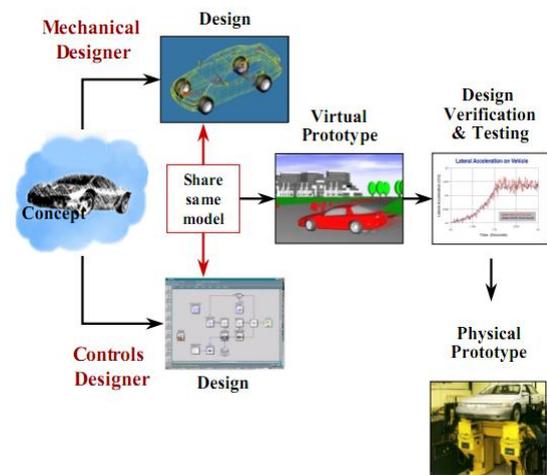


Figure 17: Co-simulation ADAMS®/MATLAB-SIMULINK®.

In “Controls” menu, we can select and set these variables values. After defining the variables, three files (.m, .cmd and .adm file) are generated from ADMAS/CONTROL, which are useful in data-exchange between ADAMS® and MATLAB® (Yi *et al.*, 2009). By executers the prompt command “ADAMS\_sys” in MATLAB® the mechanical sub-system will be generated.

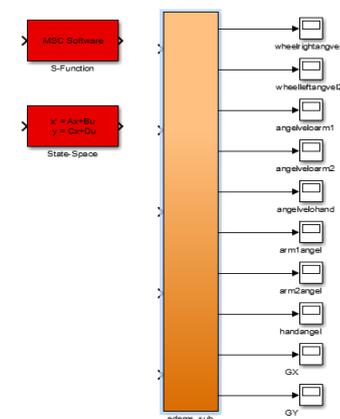


Figure 18: Connection between ADAMS® and SIMULINK® models;

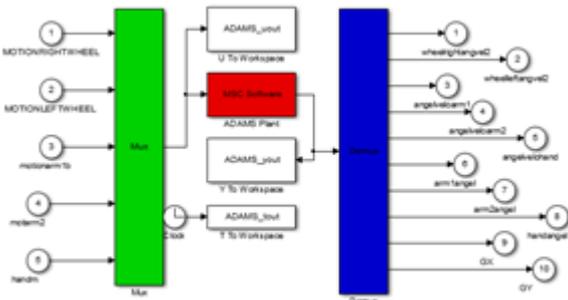


Figure 19: The input/output of model in ADAMS®

B. SIMULINK® –Based control system modelling

Based on the analysis above, robot differential drive SIMULINK® model can be further modified to include PI controller and velocity feedback to have the form shown in Fig.20.

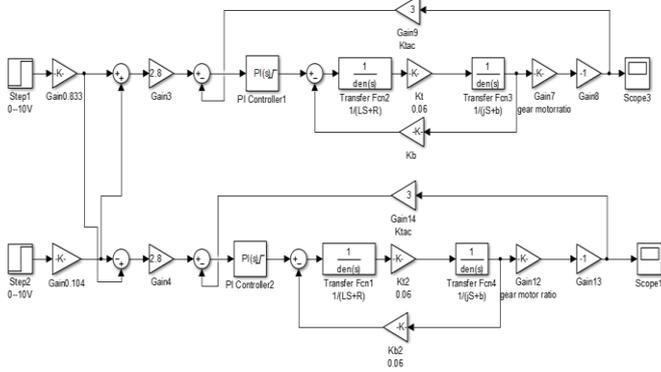


Figure 20: Robot differential drive SIMULINK® Model.

In addition, arm motors controller in SIMULINK® Model can be further modified to include PI controller and feedback to have the form shown in Fig.21.

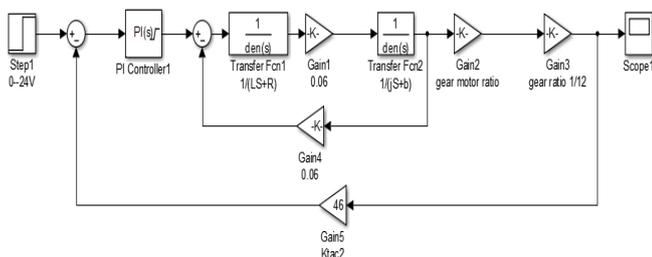


Figure 21: Arm motors controller in SIMULINK® Mode.

C. SIMULINK® based modelling

For the system model established by MATLAB®, its inputs are the output part of “ADAMS-sub”. The complete co-simulation model of the Wheeled Hybrid Mobile Robot is shown in Fig.22 is the wheeled hybrid mobile robot model produced in SIMULINK®. By importing the ADAMS-sub

block into the SIMULINK® environment, the wheeled hybrid mobile robot model becomes suitable for control and motion simulation as a defined system in MATLAB® [10].

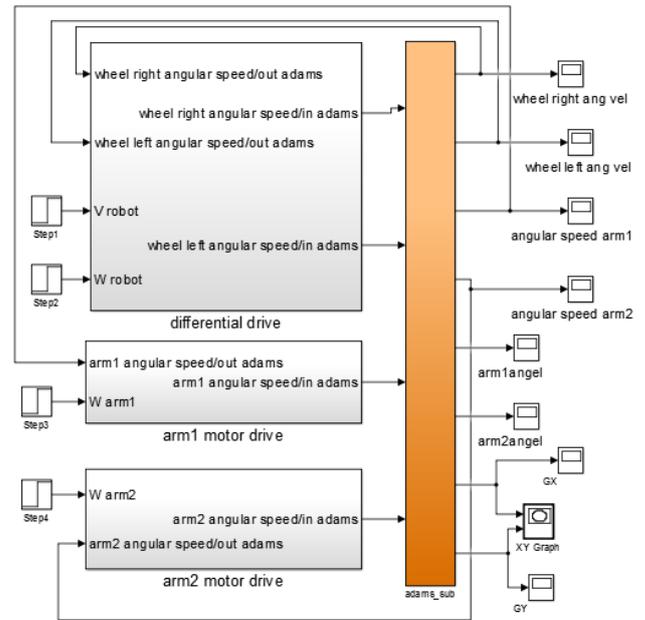


Figure 22: The wheeled hybrid mobile robot model in SIMULINK®.

D. Co-Simulation results

It is time to conduct the co-simulation. That is an interactive closed process. During the simulation, interactive process is shown on ADAMS® interface. After the implementation of co-simulation, we found:

The best values for the PI controllers are  $K_p = 0.1, K_t = 40$  for a step response without overshoot.

Comparing the control out with ADAMS\_sub out in terms of motors response and angular velocity, we found:

Angular velocity out is identical as shown in Fig.23 Response time is 0.1Sec. The measured delay of the motors response within ADAMS® environment is about 3ms.

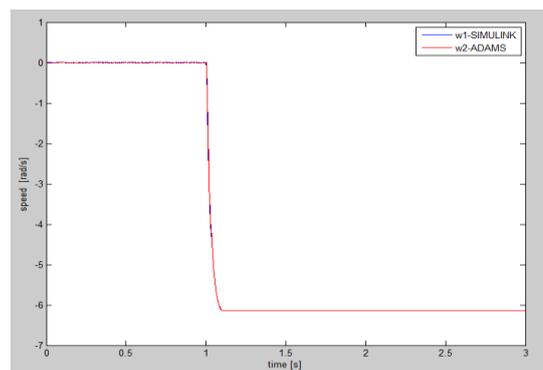
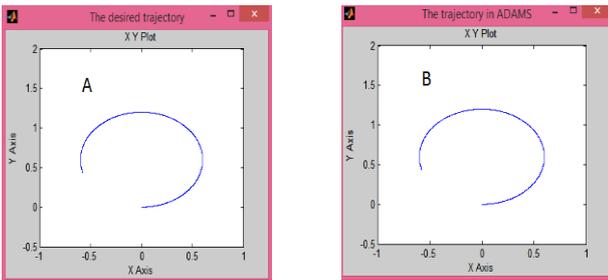


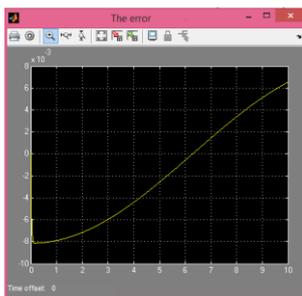
Figure 23: Comparison between the response motors in SIMULINK® and in ADAMS® environment

We also found the following results for different values of angular velocity and linear velocity and the results are in meters:

- $W=W_{max} = 0.5 \text{ rad/Sec}$  ,  $V=0.3 \text{ m/Sec}$  (Fig.24)

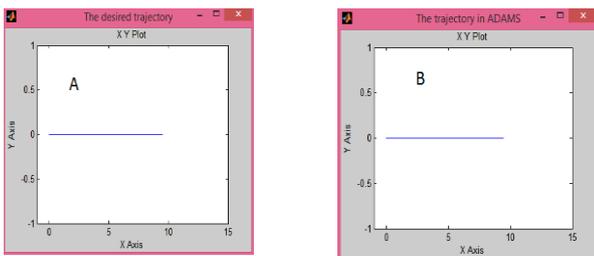


**Figure.24:** A:The desired trajectory, B: The trajectory in ADAMS®.

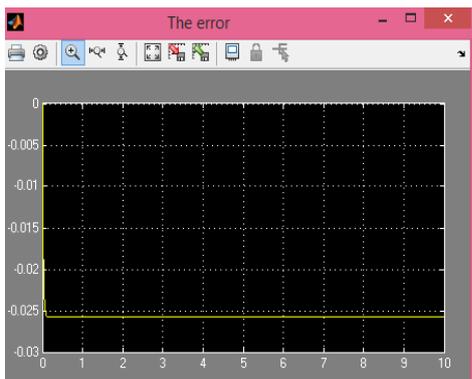


**Figure 25:** The error in trajectory.

- $V=V_{max} = 1 \text{ m/Sec}$  ,  $W=0 \text{ rad/Sec}$  (Fig.26)

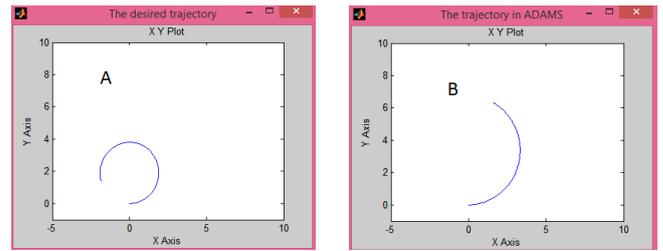


**Figure 26:** A:The desired trajectory, B: The trajectory in ADAMS®.

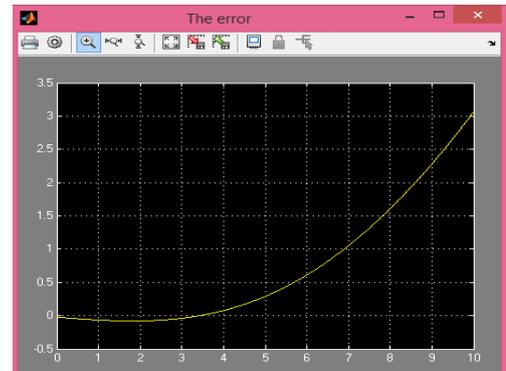


**Figure 27:** The error in trajectory.

- $W=W_{max} = 0.5 \text{ rad/Sec}$  ,  $V_{max}=1 \text{ m/Sec}$  (Fig.28)



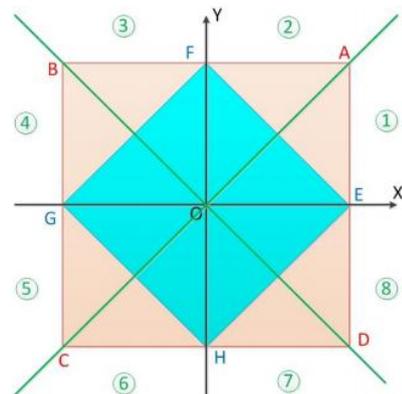
**Figure 28:** A:The desired trajectory, B: The trajectory in ADAMS®.



**Figure 29:** The error in trajectory.

Note in the first and second cases that the base robot is able to track the desired trajectory with an error of relatively small value does not exceed (0.025m) and error due to the time required to reach the engines for the speed required.

In the third case, we find that robot engines can not secure the speed required, resulting in a significant shift from the desired trajectory, In order to take advantage of the full range of the wand movement, the large square (A,B,C,D) whose surface points represent the different values of the linear and angular speed of the vehicle must be compressed into the small square (E,F,G,H) whose surface points represent the different possible values of the linear speed and angle of the vehicle's engines (Fig.30).



**Figure 30:** The difference between the speed of the vehicle and the speed of the motor

## CONCLUSION

This paper presents a model for simulation and control of Wheeled Hybrid Mobile Robot. The implementation of modelling and simulation is done by using programs CATIA®, ADAMS®, and MATLAB-SIMULINK®. We build a co-simulation model of Wheeled Hybrid Mobile Robot and we designed an interface between the software ADAMS® and SIMULINK® environment. This interface allowed us to control and simulate the dynamic behavior of different design. On the other hand, the integration of controller system with the mechanical structure modeling, the testing process is greatly simplified, and the risk of the control law being poorly matched to the real system greatly reduced.

Wheeled Hybrid Mobile Robot can go more quickly on the rugged terrain with obstacles less than 25 cm high, and have a simpler design than Tracked Hybrid Mobile Robot. Like all wheeled robots, pass stairs obstacle is a difficult process compared to Tracked Mobile Robot.

Fig (31) shows The Wheeled Hybrid Mobile Robot physical prototypes.



**Figure 31:** The Wheeled Hybrid Mobile Robot physical prototypes

## REFERENCES

- [1] R.T. Laird (SSC-SD), H. R. Everett (SSC-SD), G.A. Gilbreath (SSC-SD), R.S. Inderieden (SSC-SD), K.J. Grant (CSC), EARLY USER APPRAISAL OF THE MDARS INTERIOR ROBOT. Space and Naval Warfare Systems Center, San Diego (SSC-SD), CA 92152-7383
- [2] Explosive Ordnance Disposal Robot - KNIGHT A (Article No.: 130001). Force Ware GmbH, Arbachtalstr. 10, 72800 Eningen, Germany
- [3] R. Siegwart and I. R. Nourbakhah, Introduction to Autonomous Mobile Robots. Cambridge, MA: MIT Press, 2004.
- [4] A. Filipescu, V. Minzu, B. Dumitrascu and E. Minca, Trajectory Tracking and Discrete-Time Sliding-Mode Control of Wheeled Mobile Robot. Proceedings of the IEEE International Conference on Information and Automation, Shenzhen, China, 2011, pp. 27-32.
- [5] Goldenberg, A. A., and Lin, J., 2005, "Variable Configuration Articulated Tracked Vehicle," U.S. Patent No. 11/196,486.
- [6] P. Ben-Tzvi, Goldenberg, and J.W. Zu, "Design and Analysis of a Hybrid Mobile Robot with Compounded Locomotion and Manipulation Capability", Transaction of the ASME, Journal of Mechanical Design, vol. 130, pp.1-13, July 2008
- [7] Brezina, T.; Hadas, Z.; Vetiska, J. Using of co-simulation ADAMS®-SIMULINK® for development of mechatronic systems. In Proceedings of the 14th International Symposium, on MECHATRONIKA, Trencianske Teplice, Slovakia, 1–3 June 2011; pp. 59–64.
- [8] Zong, X.Y. and Y.Y. Li, 2005. Control simulation of robot arm based on ADAMS® and MATLAB®. Microcomput. Informat., 35: 29-30.
- [9] Liu, Y.L.; Xiang, C.L.; Wang, W.D.; Huang, K. Co-simulation of a dual-mode electro-mechanical transmission in ADAMS® and MATLAB®. In Proceedings of the IEEE International Conference on Mechatronics and Automation (ICMA), Tianjin, China, 3–6 August 2014; pp. 1096–1101.
- [10] Ben-Tzvi, P., Raoufi, C., Goldenberg, A.A., and Zu, J.W., "Virtual Prototype Development and Simulations of a Tracked
- [11] Thomas Hellström, Kinematics Equations for Differential Drive and Articulated Steering, Department of Computing Science, Umea University 28-08-2011.
- [12] Mobile Robots Moving Intelligence Edited by Jonas Buchli (2010).
- [13] Deng, Y.B.; Zhang, H.; Ma, G.H. A co-simulation of seam tracking system based on ADAMS® and SIMULINK®. In Proceedings of the Second International Conference on Mechanic Automation and Control Engineering (MACE), Hohhot, China, 15–17 July 2011; pp. 8–11.
- [14] Getting Started Using ADAMS/Controls