Analysis of Dynamic Interaction Issues for Omnidirectional Mobile Robot

G. R. Nikhade, S. S. Chiddarwar and A. K. Jha

Abstract Omnidirectional welding mobile robot (Omni-WMR) consists of a manipulator mounted on the mobile platform equipped with omnidirectional wheel. Omnidirectional mobile robots have the capability to move in any direction and hence it is finding a prominent place in many applications in manufacturing and processing industries. This capability avoids the transportation of heavy and lengthy material to the workspace. As the manipulator mounted on the mobile platform while performing the task, it is necessary to study the effect of platform motion on the dynamic behavior of manipulator and vice versa. This paper is focused on the dynamic interaction between manipulator and platform. For this, coupled dynamic model of Omni-WMR is developed. To evaluate this approach, two different case studies are presented in this paper. Results show that there is a significant change in torque values developed at manipulator joints due to the platform motion and vice versa as well as change in position of the manipulator.

Keywords Dynamic interaction · Omnidirectional · Mobile robot
Coupled dynamic

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1 Introduction

Industrial robots are mainly classified as fixed and mobile robots depending on the nature of working. In industries, it is very difficult to transport lengthy and heavy structures to the workstation because of limited space on industrial floor. In such condition, a mobile robot finds the best alternative over the fixed base robots by mounting the robot on the moving platform. It obviously increases its workspace by moving the mobile robots to the workstation. The maneuverability of mobile robots mainly depends on the type of wheels used on the platform. To achieve the omnidirectional motion, special and omnidirectional wheels are used, namely ball wheels, universal wheels, and Mecanum wheels. Among these, Mecanum wheel is having an enormous omnidirectional capability due to its structure it can perform any task within least possible floor area [1]. Moreover, along with the various advantages of mobile robots, there are certain issues like dynamic stability, structural complexity and dynamic interaction between the manipulator and omnidirectional platform needs to be resolved. To resolve these issues, a SCORBOT ER-IV manipulator is considered which is mounted on the omnidirectional platform attached with Mecanum wheel. The kinematic and dynamic modeling of the manipulator and omnidirectional platform is performed to determine the torque variation at the joints of the manipulator with and without the platform motion as well as by mounting the manipulator at different locations. Finally, the proposed approach is implemented to two different case problems. In order to comprehend the current state of the art, a detailed literature review covering various issues of dynamic interaction is presented next.

Robert and Khatib [2] developed a dynamic model of a holonomic mobile robot with powered caster wheels. They claimed that the design of the powered caster vehicle provides smooth, accurate motion with the ability to traverse through the hazards of typical indoor environments.

Carter et al. [3] developed dynamic equations of motion by Newton's second law for omnidirectional RoboCup players, assuming that no slip occurs at the wheel in the spin direction. Whereas, Williams II et al. [4] presented a dynamic model for omnidirectional wheeled mobile robots, including wheel/motion surface slip. They experimentally measured the coefficient of friction and forces responsible for a slip in order to validate their friction model. Further, Yu and Chen [5] presented a dynamic model of a non-holonomic mobile manipulator consisting of multi-degree of freedom serial manipulator and an autonomous wheeled mobile platform. They have assigned a coordinate frame to each wheel to correlate their kinematic and dynamic parameters with a world coordinate frame to develop a combined dynamic model of mobile manipulators.

Bui et al. [6] developed a dynamic model of welding mobile robot (WMR) by assuming suitable constraints with no-slip condition for the wheel. They proposed an adaptive motion tracking algorithm for the two-wheeled WMR and implemented in simulation environment as well as a real-world model. A fully coupled dynamic model of the mobile manipulator system dealing with non-holonomic constraints was developed by Gomes and Ferreira [7] using a Lagrange–Euler formulation. Further, they have implemented it to control the end-effector position of a mobile manipulator having a differential-drive platform and two degrees of freedom manipulator mounted on it.

Amagai et al. [8] developed a dynamic model and control system for omnidirectional mobile manipulator with four driving wheels to determine the relationship between the torque of the wheel and driving force generated to the platform.

Williams II et al. [9] established a novel method of motion planning in the cluttered environment for three-wheeled omnidirectional mobile robots. The environment was considered to be dynamic, wherein the obstacles were moving with general velocities without previous knowledge of motion profiles. Wang et al. [10] developed a dynamic motion control algorithm for position control and trajectory tracking of the omnidirectional mobile platform equipped with four independent omnidirectional wheels equally spaced at 90° from one to another.

From the above discussion, it is evident that most researchers have limited their work toward the development of the dynamic model of either manipulator or mobile platform equipped with either conventional wheels or simple omnidirectional wheels like caster wheel, universal wheels. It is also observed that some researchers have worked on the dynamic coupling of a manipulator with non-omnidirectional mobile platform, but the attempts to exploit the benefits of robot manipulator mounted on the omnidirectional platform equipped with Mecanum wheel for industrial applications like welding, material handling, and service application are not significant.

2 Coupled Dynamic Modeling of Omnidirectional Mobile Robot

In this section, to study the dynamic interaction between manipulator and platform, firstly the equations of motion of a robot manipulator and wheeled mobile platform are described. Then based on these equations, a method for establishing the equations of motion of a mobile manipulator which incorporates the dynamic interactions between the mobile platform and the manipulator is developed.

2.1 Dynamic Model for SCORBOT ER-IV

The dynamic model for manipulator based on L-E formulation is presented as follows:

$$\tau_{ri} = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_{r,i}}\right) - \frac{\partial L}{\partial q_{r,i}} \tag{1}$$

where L is the Lagrange function or Lagrangian which is the difference between the total kinetic energy K and the total potential energy P of a mechanical system,

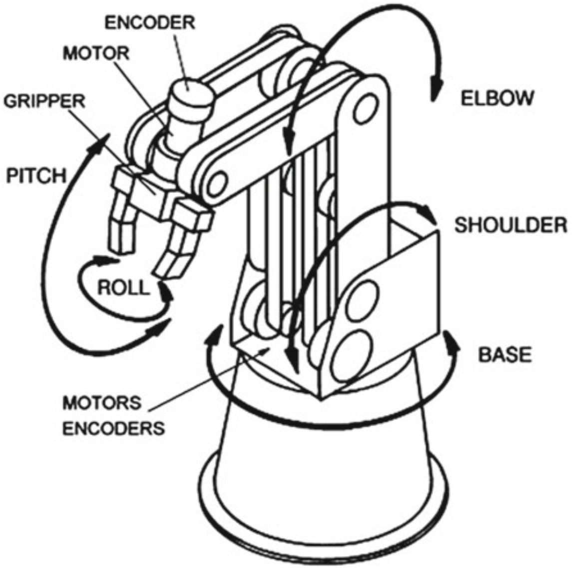


Fig. 1 SCORBOT ER-IV manipulator. *Source* Intellitek user manual

$q_r = [\theta_1(\text{base}),\ \theta_2(\text{shoulder}),\ \theta_3(\text{elbow}),\ \theta_4(\text{pitch}),\ \theta_5(\text{roll})]$ is the joint position or displacement variable of the manipulator as shown in Fig. 1. By substituting L and carrying out the differentiation, the generalized torque τ_{ri} applied to link i of an n-dof manipulator is expressed in (2) [11–13]:

$$M_r(q)\ddot{q}_r + C_r(q, \dot{q}) + G_r(q) = \tau_{ri} \tag{2}$$

where M_r is the inertia matrix of the manipulator, C_r Is the Coriolis and centrifugal term of the manipulator, G_r is the gravity loading force at joint due to link, $\dot{q}_r$ and $\ddot{q}_r$ is angular velocity and angular acceleration vector for the manipulator, respectively.

2.2 Dynamic Modeling of Omnidirectional Platform

Figure 2 shows the top view of omni-WMR platform with Mechanum wheel on which the manipulator will be mounted during the task.

To achieve the omnidirectional capability, the mobile platform is subjected constraint equation shown in (3):

$$\dot{x}cos\emptyset + \dot{y}sin\emptyset + (la)\dot{\emptyset} = R\dot{\beta}_j \tag{3}$$

where $\emptyset$ is the heading angle of the mobile robot measured from X_w axis of world coordinate system, $\dot{x}$ and $\dot{y}$ is the linear velocity of the mobile platform in x and y

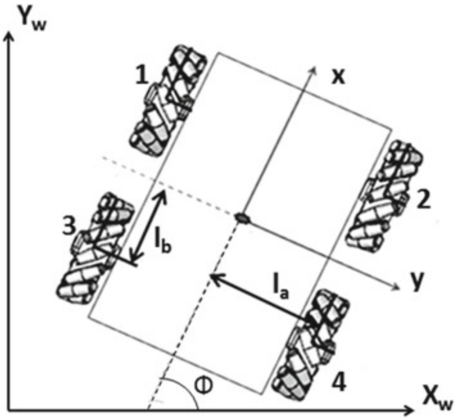


Fig. 2 Top view of omni-WMR platform with heading angle Φ

Table 1 Platform motion according to the direction and angular speed of the wheels

Direction	Wheel number			
	1	2	3	4
Forward	+	+	+	+
Backward	–	–	–	–
Right slide	–	+	–	+
Left slide	+	–	+	–
Clockwise rotation	+	–	–	+
Anticlockwise rotation	–	+	+	–
Forward–Right	0	+	0	+
Forward–Left	+	0	+	0
Backward–Right	0	+	0	+
Backward–Left	+	0	+	0

direction, respectively, R is the radius of wheel, l_a is the distance between driving wheel and vertical axis of symmetry, and $\dot{\beta}_j$ is the angular velocity of Mecanum wheels.

The constrained Eq. (3) is responsible for platform motion. The direction of platform motion depends on the direction of wheel rotation and angular speed of the wheels as shown in Table 1. '+' indicates clockwise rotation of wheel, '–' indicates anticlockwise rotation, and '0' indicates stationary wheel if seen from positive y direction.

Lagrange formulation is used to establish equation of motion for the mobile platform [14] as follows:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_{p,i}}\right) - \frac{\partial L}{\partial q_{p,i}} = Q_i - a_{1i}\lambda_1 - a_{2i}\lambda_2 - a_{3i}\lambda_3 - a_{4i}\lambda_4 \tag{4}$$

where Q_i is the generalized force (torque at each wheel), $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ are the Lagrange multipliers. a are the elements of the constrained matrix.

After substituting the Lagrange function, and carrying out the differentiation, the Eq. (4) can be arranged as

$$M_p(q)\ddot{q}_p + C_p(q, \dot{q}) = E(q)\tau_w - A^T(q)\lambda \tag{5}$$

where M_p is the inertia matrix of the platform, C_p represents Coriolis and centrifugal term of the platform, $\dot{q}_p = \left[\dot{x}\ \dot{y}\ \dot{\beta}_1\ \dot{\beta}_2\ \dot{\beta}_3\ \dot{\beta}_4\right]^T$ is linear and angular velocity vector for the platform, $\ddot{q}_p = \left[\ddot{x}\ \ddot{y}\ \ddot{\beta}_1\ \ddot{\beta}_2\ \ddot{\beta}_3\ \ddot{\beta}_4\right]^T$ is the linear and angular acceleration vector for platform, E is the constant matrix, A^T is the constraint matrix for the platform.

2.3 Dynamic Interaction Between Manipulator and Platform

The motion equations to distinguish the effect of platform motion on the manipulator and the effect of dynamics of manipulator on the platform are expressed in Eqs. (6) and (7), respectively.

$$M_r(q_r)\ddot{q}_r + C_r\left(q_r, \dot{q}_r\right) + C_{r1}\left(q_r, \dot{q}_r, \dot{q}_p\right) = \tau_{r/p} - R_r\left(q_r, q_p\right)\ddot{q}_p \tag{6}$$

where C_{r1} denotes Coriolis and centrifugal term caused by the angular motion of the mobile platform, $\tau_{r/p}$ is the input torque developed on the manipulator's joint due to platform motion, R_r is the inertia matrix which represents the effect of the platform dynamics on the manipulator.

$$\begin{aligned} M_p\left(q_p\right)\ddot{q}_p + C_p\left(q_p\ \dot{q}_p\right) + C_{p1}\left(q_r\ q_p\ \dot{q}_r\ \dot{q}_p\right) \\ = E\tau_{p/r} - A^T\lambda - M_{p1}\left(q_r\ q_p\right)\ddot{q}_p - R_p\left(q_r\ q_p\right)\ddot{q}_r \end{aligned} \tag{7}$$

where M_{p1} and C_{p1} represents the inertial term and Coriolis and centrifugal terms due to the presence of the manipulator, respectively, $\tau_{p/r}$ is the input torque to the platform, and R_p represents the inertia matrix which reflects the dynamic effect of the arm motion on the platform [15, 16].

3 Application of the Proposed Approach

This section presents the two different case studies to estimate the effectiveness of the developed approach.

3.1 Case Study 1

This case study is formulated to see the effect of dynamics of the motion of the platform on the manipulator and vice versa while executing welding task along the straight path. For this, two sub-cases are considered. In first sub-case, trajectory tracking of the omni-WMR is considered for welding of two mild steel plates having 8 mm thickness and 440 mm length by keeping the platform stationary since the path length is within the workspace of the manipulator. In the second, two mild steel plates of 8 mm thickness and 860 mm length are supposed to be welded. Since the 860 mm length is beyond the reach of the SCORBOT ER-IV, the motion of omnidirectional platform is also considered. The time required to weld these plates is 72 s, which is calculated by considering the various welding parameters like voltage, current, feed rate, etc. [17].

To obtain the smooth joint trajectories for the SCORBOT ER-IV, a cubic spline as shown in (8) is fitted to the joint trajectory obtained from IK solutions [18].

$$\theta(t) = c_0 + c_1 t + c_2 t^2 + c_3 t^3 \tag{8}$$

where, c_0, c_1, c_2, and c_3 are the coefficient of the equations obtained from the initial and the final angular position of the manipulator joint and t is the time required to finish the task. Using the above expressions, the time history plot of displacement is obtained and it is shown in Fig. 3.

These joint trajectories and the physical parameters of the SCORBOT ER-IV and the omnidirectional platform with Mecanum wheels was given as an input to the

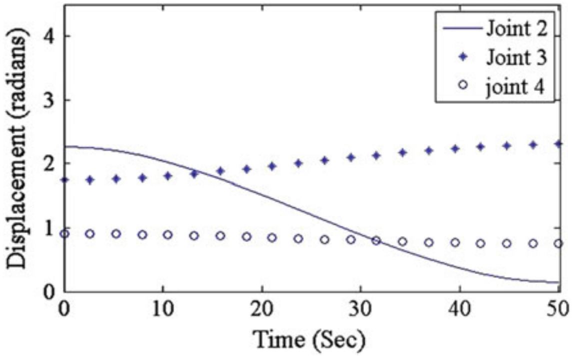


Fig. 3 Joint trajectory for straight path

Fig. 4 Torque variations at the joints of manipulator mounted on stationary platform

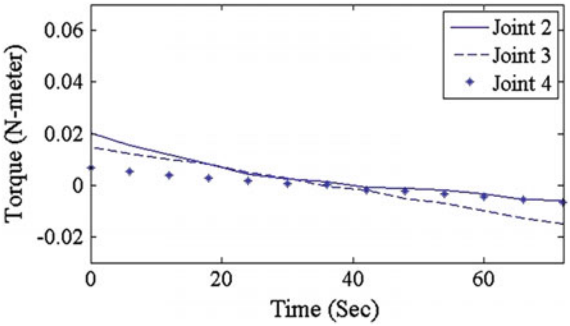
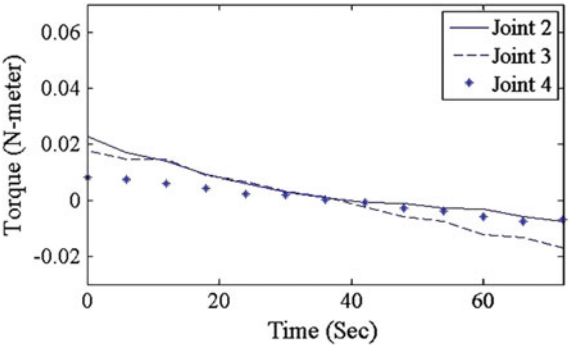


Fig. 5 Torque variations at the joints of manipulator mounted on mobile platform



developed MATLAB® program to compute the torque required at each joint of the SCORBOT ER-IV by using Eq. (6).

The torque required at each joint of the manipulator is obtained by this analysis and same are plotted in Figs. 4 and 5.

3.2 Case Study 2

In order to determine the variation in torque developed at manipulator joints as well as on platform wheel when the manipulator is positioned at different locations on the platform, another weldment (ABCDE) as shown in Fig. 6. This weldment requires zig-zag motion of welding torch attached to the end-effector of manipulator. In order to demonstrate this aspect, two sub-cases are considered.

In first sub-case, the manipulator is mounted at the center of gravity of the platform. Omni-WMR is moved in such a way that welding torch follows the double line path (AB-BC-CD-DE) and platform follows the dotted path shown in Fig. 6. The total length of the end—effector path is considered to be 600 mm and that of platform path 200 mm. In second, the manipulator is shifted by 0.125 m (*d*) from the center of

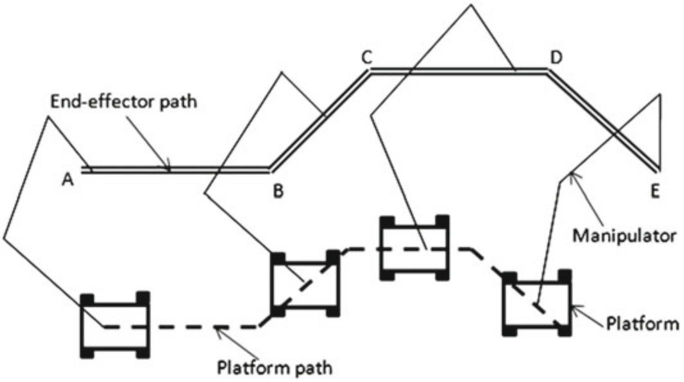


Fig. 6 Path followed by manipulator and platform to achieve weldment

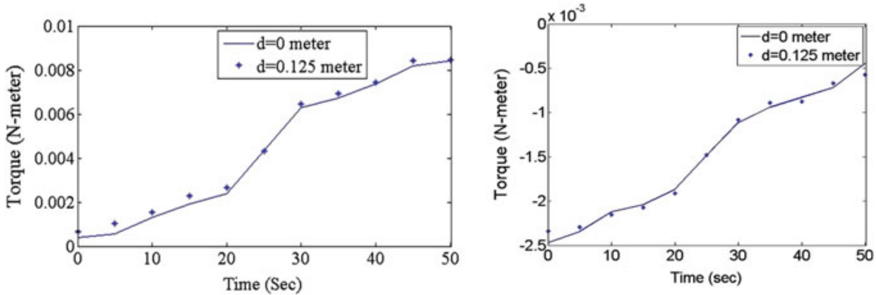
gravity of the platform. Both paths are fitted with separate cubic splines and further analysis is done as discussed in Case Study 1 [19].

Temporal information of torque at various joints of the manipulator and wheels of the platform is obtained using Eqs. (6) and (7). Figure 7 shows the comparison of torque required at joint 2(shoulder), 3(elbow) and 4(pitch), respectively, at two different positions of the manipulator.

The welding time came out to be 50 s by the same methodology used in Case Study 1. The total distance traveled by the platform during the welding of the path is 200 mm in 50 s.

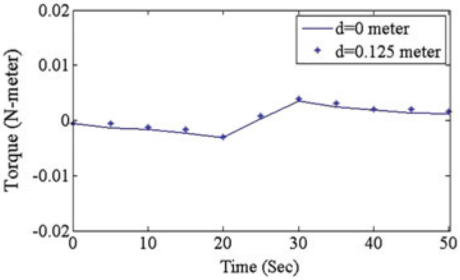
4 Results and Discussion

The analysis of case study 1 revealed that, even though displacement, velocity, acceleration and time were kept constant, the torque requirement was more for 860 mm weldment than for 440 mm weldment. It was observed that 15–30% more torque at manipulator joints is required when platform motion is also involved. From this fact, it can be inferred that the platform motion shows a considerable increase in the torque required at manipulator joints. These results justify the phenomenon of dynamic interaction between manipulator and platform. However, when the torque required for platform motion was computed, it came out to be constant. It signifies that the effect of dynamic interaction on platform wheel is uniform over all the four wheels. Moreover, when the torque requirement at the platform wheel is compared, it is found that average 53.4% more torque is required when the manipulator is mounted on platform as compared to platform without manipulator.



(a) Joint 2(shoulder)

(b) Joint 3(elbow)



(c) Joint 4(pitch)

Fig. 7 Torque developed at the joints

From case study 2, it can be concluded that the torque requirements at manipulator joint do not change with a change in the position of the manipulator. However, a different scenario was observed for omnidirectional wheels. When torque requirement at platform wheels are compared, it is observed that the 9–12% more torque developed at front wheels and 2–3% less torque at the rear wheels when the manipulator is mounted away from the mass center of platform by distance 0.125 m compared to its location exactly at the mass center. This is because of shifting the manipulator towards the front wheels of the platform. Moreover, after comparing the torque at platform wheels for forward and diagonal motion of platform, it is seen that nearly 40–50% more torque developed during diagonal motion as compared to forward motion because another pair of wheels is stationary. These results clearly indicate that the effect of the position of the manipulator is more prominent on the torque requirement at omnidirectional wheels than on the joints of the manipulator.

5 Conclusions

In this paper, a coupled dynamic model for a omnidirectional mobile robot is developed to study the dynamic interaction between omnidirectional platform and SCORBOT ER-IV. To validate this model two different case studies were considered which included the welding of straight and zig-zag path. The study of dynamic interaction between omnidirectional platform and SCORBOT ER-IV revealed the effect of motion of platform on SCORBOT ER-IV and vice versa. The equations established for each condition of interactions are the function of joint/wheel velocity, which emphasizes the severity of effect of dynamic interaction at higher velocities. Moreover, the result obtained from the developed dynamic model is validated by MATLAB simulation environment but it is out of the scope of this paper.

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