Abstract: This paper focuses on the control of a mobile manipulator comprising a combination of a mobile platform and an arm manipulator attached to it. A robust controller using an Active Force Control (AFC) strategy is performed to eliminate the effect of any disturbances present in the system. The AFC algorithm creates an estimated force or torque feedback within the AFC loop to allow for the compensation of any sudden disturbance (spike) in the dynamic system, before relaying the signal to the position/velocity controller. AFC also allows faster computational performance by using a fixed estimate of the inertia matrix ($IN$) of the system instead of considering the entire system dynamic model. A feedforward of the simplified model of the dynamic system is implemented to complement the $IN$ for a better trajectory tracking performance of the system. A computed torque control method is also considered as a benchmark to observe the robustness and performance of the proposed AFC-based model. The dynamic model of the mobile manipulator system is developed using the Lagrangian approach. A 3D simulation of the three degree of freedom (DOF) arm manipulator attached to a skid steering four wheel mobile platform is carried out to show the effectiveness of the proposed system.

Key-Words: Active force control, Feedforward control, Mobile manipulator, Model based, Robust control, Tracking performance

1 Introduction
In recent years, mobile robotics is a major focus of research environment. Two of the most research application for mobile robot is space exploration and service robot. Application for mobile robot in industrial environment is mostly limited to automated guided vehicle (AGV) and not to other more complicated task. This is probably because of the lack of suitable manipulator can be combine with the mobile robot to perform such task. Precision and reliability of a typical industrial robot arm is well proven to be an essential part in modern manufacturing processes. These industrial robot arms have a wide application range: expanding from a simple process like point-to-point material transfer to a more complicated operation, like continuous trajectory tracking, spray painting, and welding. The fixed base of the industrial robot arm limits the working range and flexibility of the system. By adding mobility to the robot arm, it can significantly increase the working range and flexibility of the robot, but at the same time, this will increase the control system complexity. Most of the recent industrial manipulators are still using PID position controller by neglecting the dynamic model of manipulator. This approach is sufficient, since most of the parameters surrounding the manipulator is controllable. Adding mobility to the manipulator, however, will change the system dynamics and may expose the system to more environmental noises, and hence, a robust control system is required.

The dynamic system of mobile manipulator is coupled which means any movement from the mobile platform will affect the arm manipulator and vice versa [1]. Yamamoto and Yun show the dynamic model of a nonholonomic mobile manipulator taking into consideration the interaction between the two. A nonlinear feedback control using an input output linearization technique was performed and the tracking performance of the system was studied. In the nonlinear feedback control the mobile manipulator nonlinear dynamic model with compensation for the dynamic interaction between the mobile platform and manipulator shows better tracking error performance. A more robust controller based on the Lyapunov’s second method was determine based on the global convergence of the tracking errors to zero.

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and boundedness of the parameter estimates. Using the Lyapunov’s second method the system stability can be determined by showing that the Lyapunov function is positive definite and continues and the derivative of the Lyapunov function is negative semi definite along the function trajectories. A global tracking controller that is based on the system dynamic tracking error and asymptotically converges to the desired trajectory was proved by the Lyapunov’s second method and extended Barbalat’s lemma in [2]. However in the Lyapunov’s second method, finding a suitable Lyapunov function can prove to be a difficult task and adjusting the control law according to the Lyapunov function sometime required a lot of trial and error procedure.

Neural network (NN) based control is a popular method used to control complex nonlinear dynamic system and increases the disturbance rejection capability of the mobile manipulator. The neural network based control typically uses a neural network estimator to identify the uncertainty of a nonlinear dynamics and compensate for it. In [3], two NN controllers were used to control the arm and mobile platform separately. The NN acted as a compensator which is combined with a linear control term. The NN compensator was determined on-line with no preliminary learning stage required. A suitable Lyapunov function was determined based on the system dynamic error for each of the mobile platform and the manipulator. The proposed NN controller shows the ability to reject the presence of some bounded disturbances but the experimental setup only considers a fixed manipulator with a fixed base. In [4, 5] an adaptive NN control based on radial basis function (RBF) was used to find a linearly parameterized approximators to approximate the system unknown nonlinearity. The proposed system considers the mobile manipulator as a whole where one NN controller was used to control the mobile manipulator. The simulation result shows the ability of the proposed system to asymptotically converge to the desired trajectories.

Active force control (AFC) is known to be capable of controlling the dynamic system with internal feedback force or torque, which is continuously estimated from the system disturbance response to compensate the effects of disturbance, and hence further improve the robustness of the system. In [6] AFC was combine with resolved acceleration control which is used to control a differential drive mobile manipulator with two-link planar arm. The resolve acceleration control manages the kinematic aspect of the system while AFC combine with a proportional integral control manage the dynamic aspect of the system. A torque sensor or an accelerometer is used to monitor the dynamic system in real time. The main advantage of AFC is the ability to simplify the dynamic model of the system into an estimated inertia matrix (IN) by utilizing the torque feedback within the dynamic system.

Several methods have been proposed to determine the appropriate inertia matrix (IN) of any particular system. A more robust form of AFC was introduced to estimate the suitable inertia matrix using various intelligent schemes including neural network, fuzzy logic, iterative learning and knowledge based methods [7-10].

A knowledge based fuzzy (KBF) was further introduced to estimate the value of the IN in [11]. In the research, it was noticed that there was a repeating pattern that shows that when the actual velocity of a joint decreases, the tracking error increases and when the velocity of a joint increase then the tracking error decreases. This observation of the system shows that the increase in error can affect the inertia of the system. A fuzzy based law to estimate the IN of the system was then developed based on the observation. The results from both simulation and experimentation show promising robustness in the control of the mobile manipulator. However, with the elaborate and intricate algorithm design applied to a rather simple AFC system, it can undermine the simplicity of the AFC itself. Thus, there is a need for a trade-off between superior robustness and real world application.

In this paper, a feedfoward control is proposed to be combined with AFC to compensate for the system inertia matrix. Feedforward control is well known to assist various motion control system improvement on the tracking performance [12]. The superiority of AFC in the motion control of a mobile manipulator to continuously track a prescribed trajectory is highlighted and as a benchmark, a comparison with another control method commonly known as computed torque control was performed. In this study, the mobile manipulator consists of a mobile platform with two DOF differentially driven system and a three DOF articulated manipulator, mounted on top of the mobile platform.

The mobile platform is located at \((x_m, y_m)\) coordinate, defined at the centre of the robot \(O_m\), in between the two wheels. \(\varphi_m\) represents the heading angle. The distance between the two wheels of the mobile platform is denoted as \(b\), whereas the wheel radius is \(R\). The distance between \(O_m\) and the base of the arm manipulator \(O\) is \(p\). The tip position of the manipulator end effector is represented as \((x_e, y_e, z_e)\), and the joint angle of the manipulator as \((\theta_1, \theta_2, \theta_3)\).
θ₃). Fig. 1 shows the diagram of the mobile platform and Fig. 2 shows the diagram of the arm manipulator.

2 Preliminaries

The main purpose of this paper is to investigate the effectiveness of AFC in trajectory tracking, and at the same time, assessing the robustness feature of the developed AFC motion controller to counteract the existing disturbances. The dynamic model and the trajectory generation for the mobile manipulator are important in showing the robustness and the trajectory tracking ability of the mobile manipulator. Although the mobile manipulator configuration is using the skid steering four wheel design, it is assumed that this configuration have the same effect as a differential drive with two wheels setup.

2.1 Dynamic Model of Mobile Manipulator

Consider the dynamic equation of a nonholonomic mobile platform as:

\[ M_p(q)\ddot{q} + C_p(q, \dot{q}) + A^T(q)\lambda + R_p(q)\ddot{\lambda} = B(q)\tau \]  

(1)

Where \( q \in R^{4x1} \) represent the generalized coordinate of mobile platform, \( q_r \in R^{3x1} \) represent the generalized coordinate of arm manipulator, \( M_p(q) \in R^{4x4} \) is the symmetric and positive definite inertia matrix of mobile platform, \( C_p(q, \dot{q}) \in R^{4x1} \) is the centripetal and Corioli’s matrix of mobile platform, \( \lambda \) is the Lagrange multiplier used to reflect the existence of constrain forces in mobile platform, \( A(q) \in R^{2x4} \) is the constrain matrix, \( B(q) \) is the input transformation matrix and \( \tau \) is the torque input. \( R_p(q) \in R^{4x4} \) is the inertia matrix which represent the mobile platform dynamic on the manipulator.

The mobile platform is subject to three constrains which is it cannot move in the lateral direction and both wheels cannot roll and slip. The constraint equations can be written as:

\[ \dot{x}_m \sin \varphi - \dot{y}_m \cos \varphi = 0 \]  

(2)

\[ \dot{x}_m \cos \varphi - \dot{y}_m \sin \varphi = \frac{R}{2} (\dot{\theta}_r + \dot{\theta}_l) \]  

(3)

This two constraint equations can be written as matrix form:

\[ A(q)\dot{q} = 0 \]  

(4)

Where

\[ A(q) = \begin{bmatrix} -\sin \varphi & \cos \varphi & 0 & 0 \\ -\cos \varphi & \sin \varphi & R/2 & R/2 \end{bmatrix} \]

It is possible to find a matrix \( S^T \) formed by a linearly independent vector field spanning the null space of \( A \) where:

\[ A(q)^T S(q)^T = 0 \]  

(5)

and there exists a smooth vector \( \eta \) such that

\[ \dot{q} = S(q)\eta \]  

(6)

\[ \ddot{q} = S(q)\dot{\eta} + \dot{S}(q)\eta \]  

(7)

Where here \( \eta = [\dot{\theta}_r, \dot{\theta}_l]^T \) and

\[ q = [x_m, y_m, \theta_r, \theta_l]^T. \]
Using (5) and (7) and by multiplying (1) with $S(q)^T$ we get:

$$S^T \left( M_p S \dot{\eta} + M_p \dot{S} \eta + C_p \right) = S^T B \tau_p - S^T R_p \ddot{q}_r$$

(8)

The dynamic equation of the arm manipulator can be given by:

$$M_r(q_r) \ddot{q}_r + C_r(q_r, \dot{q}_r) + G(q_r) = \tau_r - R_r(q_r, \dot{q}_r)$$

(9)

and similarly by substituting (7) into (9), we have:

$$M_r \ddot{q}_r + C_r + G(q_r) = \tau_r - R_r \dot{S} \dot{\eta} - R_r S \dot{\eta}$$

(10)

Here $M_r(q) \in R^{3 \times 3}$ is the symmetric and positive definite inertia matrix of the arm manipulator, $C_r(q, \dot{q}) \in R^{3 \times 1}$ is the centripetal and Coriolis’s matrix of arm manipulator, $G(q_r)$ is the gravity effect on the mobile manipulator arm, $R_r(q) = R_r(q)^T$ is the inertia matrix which represents the arm manipulator dynamics on the mobile platform.

Considering the generalized coordinate for the mobile manipulator as $q = [\theta, \theta_1, \theta_2, \theta_3]$ the generalized dynamic equation of the mobile manipulator can be given as:

$$M(q) \ddot{q} + C(q, \dot{q}) + G(q) = P \tau$$

(11)

Where

$$M(q) = \begin{bmatrix} S^T M_p S & S^T R_p \\ R & S \\ M_r \end{bmatrix}, P = \begin{bmatrix} S^T B & 0 \\ 0 & I \end{bmatrix} \text{ and}$$

$$C(q, \dot{q}) = \begin{bmatrix} -S^T M_p \dot{S} \eta - S^T C_p \\ -C_r - R_r S \dot{\eta} \end{bmatrix}$$

2.2 Controller Design

The design of a good control system for a mobile manipulator that can achieve good tracking and robust performance in terms of the noise and disturbance rejection is important. Active force control (AFC) is a technique that creates a force or torque feedback within the dynamic system that allows the control system to deal with any inevitable external disturbances presented to the dynamic system. Fig. 4 shows the block diagram of the AFC controller. $\theta_{ref}$ is represented by a vector of the generalized coordinate of the mobile manipulator $(\theta, \theta_1, \theta_2, \theta_3)$. $K_m$ is the motor torque constant for each joint and wheels. $Q$ is denoted as the external disturbances applied to the mobile manipulator system. One of AFC advantages is in terms of reducing the mathematical complexity of the modelled inertia matrix of the system. $IN$ in Fig.4 represents the estimated inertia matrix where a set of parameters is used to replace the complex mathematical model of an inertia matrix. In this paper, the inertia matrix parameters were estimated using the crude approximation method.

Since in this method, the optimum value of $IN$ is fixed it can only be effective if the nonlinearity of $M(q)$ is not too complex. If the $M(q)$ is highly nonlinear, then some other methods of estimation are needed. In this paper, a feedforward value of $M(q)$ is proposed to be combined with the crude approximation method to compensate for the nonlinear effect. Fig. 4 also shows the block diagram of an AFC system with feedforward model based control. To highlight the advantages of the proposed AFC method, a more conventional control method which is known as computed torque controller was also implemented. Both of the AFC and the computed torque control methods are required to be coupled with a position controller. In this study, resolved acceleration controller is used to provide the position control of the system.

3 Simulation and results

The simulation was performed using MD Adams for dynamic model simulation and MATLAB/Simulink for control system implementation. A 3D solid model of the proposed mobile manipulator was designed in MD Adams as shown in Fig. 3.
The mobile manipulator model in MD Adams receives five input torques for each of the revolute joint \((\theta_r, \theta_l, \theta_1, \theta_2, \theta_3)\) and produces the outputs related to the displacement, velocity and acceleration of the revolute joint, all in MATLAB/Simulink environment. The proposed control algorithm was then implemented and tested. The parameters used in the simulation are: 
\[ m_p = 2.9 \text{ kg}, \quad m_w = 1.5 \text{ kg}, \quad m_1 = 1 \text{ kg}, \quad m_2 = 1.3 \text{ kg}, \quad m_3 = 0.25 \text{ kg}, \quad a_2 = 0.3 \text{ m}, \quad a_3 = 0.36 \text{ m}, \quad p = 0.1 \text{ m}, \quad R = 0.2 \text{ m}, \quad b = 0.29 \text{ m} \]
where \(m_p\) is the mass of the platform, \(m_w\) is the mass of the wheel with motor, \(m_1\) is the mass of Joint 1 (of the arm manipulator) and \(m_2\) is the mass of Joint 2.

In this simulation, the mobile platform is commanded to move in a straight line while the arm manipulator was commanded to swing in a sinusoidal motion at Joint 1. Joints 2 and 3 of the arm manipulator cause the downward motion until it stops at a fixed point. The simulation was conducted in two conditions: the first used the feedforward model based AFC to control the mobile manipulator; the second uses the computed torque control to control the system. Fig. 5 shows the tracking error result of the mobile manipulator left and right wheels. The result shows that the feedforward model based AFC performs significantly better than the computed torque. The error for the AFC is much lower than the computed torque control. Fig. 6 shows the tracking error result for the mobile manipulator arm at Joint 1 which is moving in a sinusoidal swinging motion. Although the difference in the tracking error between AFC and computed torque is not significant, the improvement in terms of less noise vibration generated by the feedforward model based AFC can be observed. Fig. 7 shows the tracking error result for the mobile manipulator arm at Joint 2 which is moving in a downward motion and then is stopped at a fixed position. The control of Joint 2 is where the dynamic effect of the mobile manipulator is at its highest and from the result, it can be seen that the feedforward AFC performs almost the same as the computed torque with slightly better noise rejection performance. Fig. 8 shows the tracking error result for the mobile manipulator arm at Joint 3 which is also moving in a downward motion and then is stopped at a fixed position. Here also, it can be seen that the feedforward AFC performs better than the computed torque in terms of the tracking error and noise rejection performance.

Fig. 4 Block diagram of feedforward model based AFC controller

Fig. 5 Tracking error for the mobile manipulator wheels

Fig. 6 Tracking error for Joint 1 of the mobile manipulator
4 Conclusion

The advantages of the feedforward AFC-based model compared to the computed torque control of the mobile manipulator were highlighted in which it is clearly shown that the former exhibits a much better trajectory tracking performance. It can also be seen that the AFC scheme demonstrates better noise rejection capability and faster computational time compared to the computed torque control by using $IN$ as the estimated inertia matrix instead of considering the dynamic model of the whole system.

References:


