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Performance Investigations of an Improved Backstepping Operational-space Position Tracking Control of a Mobile Manipulator

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ABSTRACT

This article implies an improved backstepping control technique for the operational-space position tracking of a kinematically redundant mobile manipulator. The mobile manipulator thought-out for the analysis has a vehicle base with four mecanum wheels and a serial manipulator arm with three rotary actuated joints. The recommended motion controller provides a safeguard against the system dynamic variations owing to the parameter uncertainties, unmodelled system dynamics and unknown exterior disturbances. The Lyapunov's direct method assists in designing and authenticating the system's closed-loop stability and tracking ability of the suggested control strategy. The feasibility, effectiveness and robustness of the recommended controller are demonstrated and investigated numerically with the help of computer based simulations. The mathematical model used for the computer-based simulations is derived based on a real-time mobile manipulator and the derived model is further verified with an inbuilt gazebo model in a robot operating system (ROS) environment. In addition, the proposed scheme is verified on an in-house fabricated mobile manipulator system. Further, the recommended controller performance is correlated with the conventional backstepping control design in both computer-based simulations and in real-time experiments.

Keywords: Adaptive control; backstepping design; operational-space motion control; mobile-manipulator; kinematic redundancy; disturbance observer

1. INTRODUCTION

Electronic commerce may have revolutionised shopping, but it still dependent on dozens of people flying away in warehouses to get the goods shipped out to consumers. Several companies like amazon and many more top ranking shipping industries employ workers over last year's holiday rush to fulfill their requirements. To avoid the huge rush in these shipping companies, the warehouses and shipping within warehouses are becoming programmed. Companies wasted millions of money to install several robots and linked systems for the warehouse automation. Instead of manual workers are going to the shelves and picking out items, the mobile robots with manipulators are playing a good role in these industries for the picking, placing and shipping the required items. Mobile manipulators are robotic systems where the robotic manipulators mounted on mobile platforms. These mobile manipulators are one of the essential requirements for the large-size warehouses, since the warehouses do not run on the principle of assembly-line hence; conventional fixed manipulators cannot be used. The main assignment involved in these warehouses are placing and collecting of distinct objects throughout the day with a fluctuating order speed which requires both locomotion and manipulation. For catering such demands a robust mobile manipulation along with an excellent tracking performance is required. In normal operations, almost 60% of total operation cost is spent on the mobile manipulators and their functions[1]. In real time, the mobile manipulator has to follow its distinct desired path and trajectory. There are many control schemes used to construct the trajectory performance of the system.

In the state of the art, the literature reveals that many researchers have successfully devised algorithms in motion control for good tracking performance of fixed manipulators. However, it is strenuous to attain a good performance in case of a mobile manipulator due to the uncertain nature and dynamic variations of the system. Due to unknown payload which deviates with structural uncertainty arises while state inequality appears in the workspace. Hence nowadays for uncertain systems designing a motion control scheme develops into a significant area of research.

From the recent years many investigators have been concentrating on different control schemes for finding the good trajectory tracking performance. In particular as discussed[2], it is not required to be familiar with the uncertainties in nonlinear upper bound functions. Construction of the controllers in the state-feedback form can be linear in the state, with the self -tuned time fluctuating gain control used in the adaptive laws. The recursive backstepping method based on the Lyapunov's direct method based scheme proposed around 1990s by Krstic, Kanellakopoulos and Kokotovic as discussed[3]. The elementary objective[4] is to propose a motion control scheme which can record the stated end-effector trajectory in operational-space against internal and external ambiguities.

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In[5]the paper explains the control problem for a semi-strict nonlinear system depending on unidentified parameters, ambiguity, and input constraint. Reference[6] describes an explicitly novel nonlinear control backstepping based law have been designed to incorporate a continuous-time adaptive backlash inverse model. The controller is a combination of backstepping control and Lyapunov's redesign. In[7] when correlated with the adaptive control scheme for uncertain nonlinearities and disturbances, this makes control robust andnonlinear systems approach becomes appealable. Without requiring any bounds on the unknown parameter[8]an adaptive backstepping organised process for tracking the motion control design of second-order nonlinear systems is refined. The principle of adaptive backstepping[9] is capable of solving the setback of unmeasured states and declares the close-loop system stability. A control design method for nonlinear systems of uncertain class which is robust adaptive is proffered[10-13]with disturbance observer, actuators uncertainties and backstepping method. Apart from the global stability, the paper[12] also provides L_2tracking error performance for design. A planning and control methodology has been declared[14] without outraging the non-holonomic constraints. Papers[15-17] introduces a robust adaptive control system for non-holonomic mobile robots for nonlinear systems with uncertainties. Improved backstepping design[18] can restrain from repeated differentiation problem which emerges in applying the traditional backstepping algorithm.In[19,20] the main objective is to introduce a dynamic interaction and disturbance observer so as to compensate with the environment. According to[19] in coordinated control of mobile manipulator there are no studies which consider the effect of dynamic interaction. In[21-22] these papers address the position control with kinematic and dynamic uncertainties as well as the adaptive backstepping design task-space control. According[23-24] to hybrid adaptive-fuzzy controller in the latency of uncertainties and disturbances together can track the desired trajectory and avoid the obstacles during the trajectory tracking.In[25]this paper robust task-space motion control strategy has been proposed which is capable in handling the effects of interactions with the environment.Paper[26]discusses about the redundancy resolution which helps in avoiding singularities and joint limits and also aids in increasing the Cartesian mechanical rigidity of robot manipulators. In[27-28] authors tried to comparison between nonlinear controller classic linear kinematic controller where they found nonlinear controller is harder to tune and guarantees whole-body asymptotic stability and linear programming is economical but generates more abrupt control signals.These[29-30] papers analyses work related to mobile manipulators complex task execution in order to attain the desired trajectory by refraining high tracking errors which can be executed in operational-space. Lyapunov's stability is achieved by fulfilling the constraints and providing a singularity and collision free trajectory of the system.

The primary motivation of the paper is to suggest an improved adaptive based backstepping design control scheme which displays better performance in comparison with the traditional backstepping control strategy under kinematic and dynamic constraints[31-37]. In order to obtain dexterous control of holonomic and nonholonomic mechanical systems[22] our main aim is to control task-space positions and also to overcome parametric uncertainties of the dynamic equation an improved adaptive control has been introduced in our work.

Therefore, an improved adaptive backstepping design is proffered as a robust controller in this paper. This motion control design assures the global asymptotic stability and tracking error convergence for the slowly varying perturbations and ambiguities. The recommended strategy is effectively explained numerically with the help of real-time mobile manipulator parameters.

The outline of paper is: description of mobile manipulator dynamic model is in Section 2;motion control strategy of the recommended controller is explained with Lyapunov's Stability in Section 3. In Section 4 efficacy evaluation with real time results and discussions of the suggested control method is described and deliberated. Lastly, Section 5 describes the paper with the scopes of future works.

2. MOBILE MANIPULATOR DYNAMIC MODEL

For analysis, in this study the mobile manipulator subsists of a three link manipulator fixed on a four-mecanum wheeled vehicle base serially. Mobile manipulator vehicle base is steered by the four independent motored wheels. The photographic representation and kinematic frame setup of mobile manipulator depicted in Figure 1, here, earth-fixed (inertial) frame is O (0, 0, 0), moving base frame is B (x_B, y_B, z_B) and the end effect or frame is denoted as $T(x_t, y_t, z_t)$. According to Newton–Euler recursive method the dynamic equation of motion is defined below:

$$M(q)\ddot{q} + n(q,\dot{q}) + g(q) = \tau \quad (1)$$

In equation (1) $q \in \Re^{6\times1}$ is the configuration (joint) space position variables vector, $q = [\zeta \quad \xi]^T \cdot \zeta \in \Re^{3\times1}$ is vehicle base positions and orientation vector which is penned

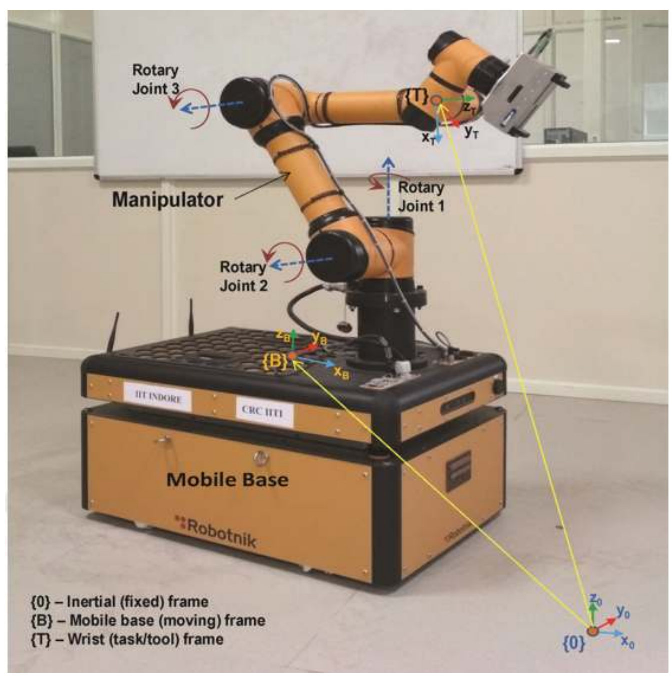

Figure 1. Kinematic frame arrangement of the mobile manipulator.

as: $\zeta = [x \quad y \quad \psi]^T$; $\xi \in \Re^{3\times1}$ is the vector of manipulator rotary joint angles which is stated as: $\xi = [\theta_1 \quad \theta_2 \quad \theta_3]^T$; the vehicle base translation positions and heading (yaw) angular displacement are x, y and ψ. θ_1, θ_2 and θ_3 are manipulator joint angles interconnected with serial manipulator links. $\dot{q} \in \Re^{6\times1}$, The configurationally space velocities and accelerations vector are expressed as $\ddot{q} \in \Re^{6\times1}$. $M(q)\ddot{q}$ is the vector of inertial matrix of the mobile manipulator, dissipative and the vector of non-conservative forces is defined as $n(q,\dot{q})$ whereas $g(q)$ is gravity effects vector of the mobile manipulator. $\tau = [\tau_b \quad \tau_m]^T \in \Re^{6\times1}$ is defined as the vector of control inputs, where $\tau_b \in \Re^{3\times1}$ is the inputs of the vehicle base vector and $\tau_m \in \Re^{3\times1}$ is the vector of input torques of the manipulator arm anchored upon vehicle platform serially. The vector of inputs can be additionally treated as two variables in consideration of control inputs and disturbances.

$$\tau = \tau_{ct} + \tau_{dis} \tag{2}$$

$$\tau_{dis} = \tau_{edis} + \tau_{idis} \tag{3}$$

$$\begin{aligned}\tau_{idis} = &\left(\hat{M}(q) - M(q)\right)\ddot{q} + \left(\hat{n}(q,\dot{q}) - n(q,\dot{q})\right) \\ &+ \left(\hat{g}(q) - g(q)\right) - F(q,\dot{q}) + \delta\end{aligned} \tag{4}$$

where, $\hat{M}(q)$, $\hat{n}(q,\dot{q})$ and $\hat{g}(q)$ are known (inaccurate) model equations of the mobile manipulator. $F(q,\dot{q})$ is the vector of frictional effects which consists of static, coulomb and viscous frictional effects δ is the internal disturbances vector familiar with the system due to measurement and process noises. τ_{edis} is the vector of external disturbances acting on the mobile manipulator. τ_{edis} is the vector of internal disturbances due to frictional effects, parameters and system uncertainties, disturbances occurred due to process noises and measurement.

2.1 Actuator and its Allocations

Input (control) vector can be rewritten for interconnecting the generalised input vector along with the single force actuator inputs of the suggested system is as follows:

$$\tau_{ct} = B\kappa \tag{5}$$

where, $B \in \Re^{6\times7}$ is the matrix of actuator configuration and $\kappa \in \Re^{7\times1}$ is the actuator inputs vector. There commended mobile manipulator has three rotary actuators at the manipulator arm and four actuator inputs in mobile base.

Putting (5) in (1) and reorganising, it provides

$$\ddot{q} = M(q)^{-1}(B\kappa - \eta + \tau_{dis}) \tag{6}$$

where, $\eta \in \Re^{6\times1}$ and $\eta = n(q,\dot{q}) + g(q)$

For the desired manipulator motion, vectors of operational-space position, velocity and acceleration in the Cartesian (task) space can be insinuated as:

$$\begin{aligned}\mu &= fun(q) \\ \dot{\mu} &= J_1(q)\dot{q} \\ \ddot{\mu} &= J_1(q)\ddot{q} + \dot{J}_1(q)\dot{q} \\ \ddot{\mu} &= J_1(q)M(q)^{-1}(B\kappa - \eta + \tau_{dis}) + \dot{J}_1(q)\dot{q}\end{aligned} \tag{7}$$

where, $\mu \in \Re^{3\times1}$ is the operational-space position vector and $\mu = [p_x \quad p_y \quad p_z]^T$. Jacobian matrix is expressed as $J_1(q) \in \Re^{3\times6}$.

Though, the mobile manipulator includes two coordinate frames and the configuration space velocities can be mapped with body-fixed frame velocities as:

$$\dot{q} = J_2(q)v \tag{8}$$

where, $v \in \Re^{6\times1}$ is the body-fixed frame velocities. Thus, operational-space velocities can be rephrased with body-fixed velocities is stated as:

$$\dot{\mu} = J_1(q)J_2(q)v = J(q)v \tag{9}$$

2.2 Kinematic Model of the Mobile Manipulator

The proffered mobile manipulator comprises 3degree of freedom (dof) of vehicle platform and a 3-dof serially connected manipulator. Figure 2 represents the joint frame arrangement. Cylindrical in shape configuration with serial arrangement manipulator links are considered in the figure. {I} is the Inertial frame and {M} is the mobile base frame. ${}^0_BT$ is the Transformation matrix from inertial frame to mobile base frame, where x_v, y_v are the translations of the vehicle in the direction of x and y and d_v is the depth of the vehicle or mobile platform.

Using the Denavit-Hartenberg formulation[35] kinematic modelling of the manipulator system is formulated which is written as:

$$\mu = \begin{bmatrix} x_v - d_2\sin(\theta_1 + \theta_v) + L_v\cos\theta_v \\ +d_4\cos(\theta_1 + \theta_v)\sin(\theta_2 + \theta_3) + L_2\cos(\theta_1 + \theta_v)\cos\theta_2 \\ y_v + d_2\cos(\theta_1 + \theta_v) + L_v\sin\theta_v \\ +d_4\sin(\theta_2 + \theta_3)\sin(\theta_1 + \theta_v) + L_2\sin(\theta_1 + \theta_v)\cos\theta_2 \\ d_1 + d_v + d_4\cos(\theta_2 + \theta_3) - L_2\sin\theta_2 \end{bmatrix} \tag{10}$$

3. CONTROLLER DESIGN

An augmented backstepping design is presented to follow accurately a given desired operational-space position trajectory of the mobile manipulator in the latency of system disturbances and ambiguities. Backstepping is a versatile nonlinear control technique which is simple to design, since it indulges a recursive method to forge the nonlinear control law along with the admissible Lyapunov's functions. Furthermore, it has weightiness of denying all the unpredictable nonlinearities, whereas safeguarding the nonlinearities in the system that can be utilised to stabilize it, thus it is truly different from other nonlinear control techniques. The major objective of the proffered controller is that the zero error convergence and the controller should overcome and adapt itself from all the problems related with the system that is, variations in

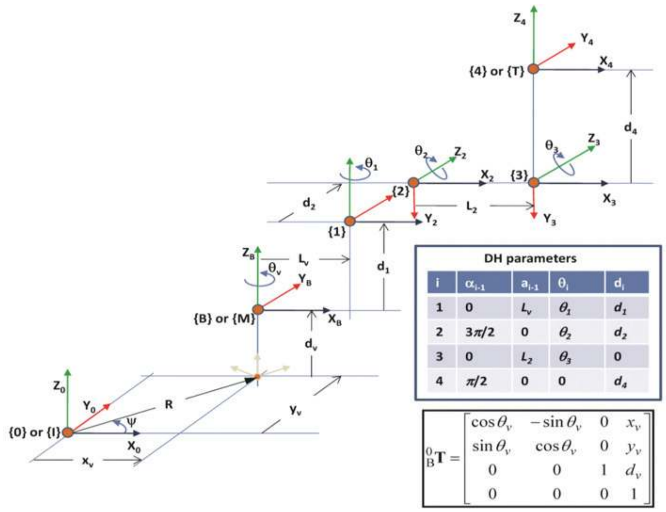

Figure 2. Denavit-Hartenberg representation of theJR2 mobile manipulator.

parameters, frictional effects, external and internal disturbances, unmodelled dynamics, etc. The suggested backstepping design with a nonlinear disturbance observer evaluates the disturbance vector based on the identified dynamics of the system, imprecise parameters of the system. The proffered observer surmises the disturbance vector which compensates the next step response based on current state measurements. To validate the closed-loop stability of the system Lyapunov's method is used. Below given presumptions are kept in mind for controller design to represent the asymptotic convergence property of the designed controller they are as follows:

Presumption 1: Controller gain matrix and observer gain matrix are believed to be symmetric positive definite matrices viz.

$$K_1 = K_1^T > 0; K_2 = K_2^T > 0; K_3 = K_3^T > 0; \tag{11}$$

These gains are presumed as positive diagonal matrices for simplicity in the numerical investigation which is stated as:

$$K_1 = k_1 I_{3\times 3}; K_2 = k_2 I_{6\times 6};\ K_3 = k_3 I_{6\times 6}; \\ k_1 > 0, k_2 > 0, k_3 > 0. \tag{12}$$

Presumption 2: The value of total lumped disturbance vector is capriciously large, bounded (since, the actuators have limited capabilities, it is assumed that the disturbances are bounded) and gradually changing along time namely. $\dot{\tau}_{dis} \approx 0$. This presumption is not practically unswerving but hypothetically it is not immensely limiting and usually presumed in research articles[2].

The system is confined to follow the given operational-space position trajectory and desired operational-space trajectory is treated as ì $_d$. The system dynamic model is rephrased as two single order sub-systems in a control-affine form defined below:

$$\dot{x}_1 = \dot{\mu} = J(x_1)\, x_2 \\ \dot{x}_2 = \dot{q} = M(x_1)^{-1}(B\kappa - \eta(x_1, x_2) + \tau_{dis}) \tag{13}$$

Here, $x_1 = \mu$ and $x_2 = q$ are state variables and will be available as state feedback signals to the motion controller. $x_1 = [x \quad y \quad z]^T$ and $x_2 = [u \quad v \quad r \quad \dot{\theta}_1 \quad \dot{\theta}_2 \quad \dot{\theta}_3]^T$. For the appropriate selection of x_2 can stabilize the first subsystem and permit the sub-system μ to track the given desired position trajectory, ì $_d$. Nevertheless, x_2 is the state vector and available as feedback to the controller and controller cannot select other values. Hence, the controller selects a virtual control vector namely x_2^{vc} and the state x_2 should follows the given, x_2^{vc}. With an appropriate input vector this action can be regulated by the second sub-system. From these actions, the closed-loop system contains three error state vectors namely,

$$e_1 = x_{1d} - x_1 \\ e_2 = x_2^{vc} - x_2 \\ e_3 = \tau_{dis} - \hat{\tau}_{dis} \tag{14}$$

where, x_{1d} denotes desired operational-space position vector μ_d. x_2^{vc} depicts virtual control input vector or in other words virtual reference vector of velocities. $\hat{\tau}_{dis}$ is the estimated disturbances vector .

In order to design the motion control for the mobile manipulator, consider a positive Lyapunov's candidate function as follows:

$$V(e_1, e_2, e_3) = \frac{1}{2}\left(e_1^T e_1 + e_2^T e_2 + e_3^T K_3^{-1} e_3\right) \tag{15}$$

where, K_3 is a design matrix which is presumed as a symmetric positive definite matrix. Here $V(e_1, e_2, e_3) \geq 0$ as it is the sum of the individual positive values.

Further, differentiating the Lyapunov'scandidate function analogous to time in together along state trajectories, it gives,

$$\dot{V}(e_1, e_2, e_3) = e_1^T \dot{e}_1 + e_2^T \dot{e}_2 + e_3^T K_3^{-1} \dot{e}_3 \tag{16}$$

where $\dot{e}_1, \dot{e}_2$ and $\dot{e}_3$ are the error derivatives. The error derivatives can be written as follows:

$$\dot{e}_1 = \dot{x}_{1d} - \dot{x}_1; \dot{e}_2 = \dot{x}_2^{vc} - \dot{x}_2; \dot{e}_3 = \dot{\tau}_{dis} - \dot{\hat{\tau}}_{dis}; \tag{17}$$

$$\dot{e}_1 = \dot{x}_{1d} - J(x_1)x_2, x_2 = x_2^{vc} - e_2 \tag{18}$$

$$\dot{e}_1 = \dot{x}_{1d} - J(x_1)x_2^{vc} + J(x_1)e_2 \tag{19}$$

After choosing appropriate stabilising function to the virtual control input in (19) as follows:

$$x_2^{vc} = J^+(x_1)(\dot{x}_{1d} + K_1 e_1), K_1 = K_1^T > 0 \tag{20}$$

where, $J^+(x_1)$ denotes pseudo inverse of the Jacobian matrix. Substituting (20) in (19), gives,

$$\dot{e}_1 = -K_1 e_1 + J(x_1)e_2 \tag{21}$$

Similarly, error derivative of $\dot{e}_2$ can be indicated as follows:

$$\dot{e}_2 = J^+(x_1)(\ddot{x}_{1d} + K_1\dot{e}_1) + \dot{J}^+(x_1)(\dot{x}_{1d} + K_1 e_1) \\ - M(x_1)^{-1}(B\kappa - \eta(x_1, x_2) + \tau_{dis}) \tag{22}$$

Select a control vector as follows:

$$\tau_{ct} = B\kappa = \hat{M}(x_1)\begin{pmatrix} J^{+}(x_1)(\ddot{x}_{1d} + K_1\dot{e}_1) + \dot{J}^{+}(x_1) \\ (\dot{x}_{1d} + K_1 e_1) + K_2 e_2 + J^{T}(x_1)e_1 \end{pmatrix} + \hat{\eta}(x_1, x_2) - \hat{\tau}_{dis} \quad (23)$$

where, K_2 denotes controller gain matrix which is presumed as a symmetric positive definite matrix viz. $K_2 = K_2^T > 0$. Substituting (23) in (22) gives,

$$\dot{e}_2 = -J^T(x_1)e_1 - K_2 e_2 - e_3 \quad (24)$$

The error derivative of $\dot{e}_3$ is given as :

$$\dot{e}_3 = \dot{\tau}_{dis} - \dot{\hat{\tau}}_{dis} \quad (25)$$

where select an adaptive law based on velocity feedback is given below:

$$\hat{\tau}_{dis} = K_3\hat{M}(x_1)x_2 + x_3$$
$$\dot{x}_3 = -K_3\left(\tau_{ct} - \hat{\eta}(x_1, x_2) + \hat{\tau}_{dis} + e_2\right) - K_3\dot{\hat{M}}(x_1)x_2 \quad (26)$$

Substituting (25) in (24), gives

$$\dot{e}_3 = \dot{\tau}_{dis} - K_3(e_3 - e_2) \quad (27)$$

As, the mobile manipulator moves gradually and its disturbance vector is also fluctuating deliberately, viz. $\dot{\tau}_{dis} \approx 0$. This presumption trims (27) as expressed:

$$\dot{e}_3 = -K_3(e_3 - e_2) \quad (28)$$

Substituting (21), (24) and (28) in (17) gives,

$$\dot{V}(e_1, e_2, e_3) = -\left(e_1^T K_1 e_1 + e_2^T K_2 e_2 + e_3^T e_3\right) \quad (29)$$

The time derivative of the Lyapunov's candidate function is negative definite which means, the selected control design is globally asymptotically stable and error tends to become nil asymptotically.

If the disturbance vector $\dot{\tau}_{dis}$ is not slowly varying and it is bounded, the selected K_3 can assures the system stability.

$$\dot{V}(e_1, e_2, e_3) = -\left(e_1^T K_1 e_1 + e_2^T K_2 e_2 + e_3^T e_3\right) + e_3^T K_3^{-1}\dot{\tau}_{dis} \quad (30)$$

4. EFFICACY ASSESSMENT

4.1 Architecture of the Entire Task with the System

To authenticate the effectiveness of the recommended motion control design, MATLAB/Simulink package is used for analysing the performance in operational-space position tracking of the mobile manipulator. Table 1 presents the specifications and the physical parameters of the mobile manipulator. The dynamic parameters considered for the simulations are obtained as per the actual mobile manipulator particularly, JR2. The motion control strategy of the current JR2 is not compatible for the users. Further, the proposed operational-space position tracking control requires the positional vector feedback of the wrist (position vector of the fourth joint of the JR2), which is not available at this time. Therefore, although the real-time robot available with the authors, the real-time validation could not perform and present in this paper. Moreover, the real-time enactment of the designed controller on a real-time mobile manipulator is considered as a future work and it will be available in near future. The real-time image of JR2 mobile manipulator in addition along its working environment is presented in Figure 3. The JR2 consists of an open architecture Robot operating system and Player/Stage Embedded PC with Linux Real Time RBK-IMU (integrated IMU + MAGNETOMETER + GYRO) with RBK-Rotary encoders. In the photographic representation the JR2 vehicle-manipulator in addition along its kinematic control package, particularly, Move It software in the lab environment is displayed. Move it is most widely used state of the art software used for the mobile manipulation and establishing modern advances in the motion planning. Gazebo package environment is used for verifying the derived dynamic model in the virtual robot model. Figure 4 represents the JR2 mobile

Table 1.Technical Parameters of the Mobile Manipulator

Parameters	Values
Size of the mobile base	800 mm x550 mm x420 mm
Maximum speed of the mobile base	3 m/s
Number of wheels	4
Number of manipulator axes	6
Work envelope of the manipulator	0.629 m^3
Horizontal distance between the vehicle frame to the manipulator base (L_v)	0.3 m
Vertical distance between the vehicle frame to the manipulator base (d_1)	0.258 m
Vehicle frame from the ground (height) (d_v)	0.42 m
Joint distance of the manipulator's second frame (d_2)	0.15 m
Joint distance of the manipulator's fourth frame (d_4)	0.109 m
Max. payload for the manipulator	2 kg
Length of the manipulator second link ($L2$)	0.408 m
Length of the manipulator third link (L_3)	0.372 m

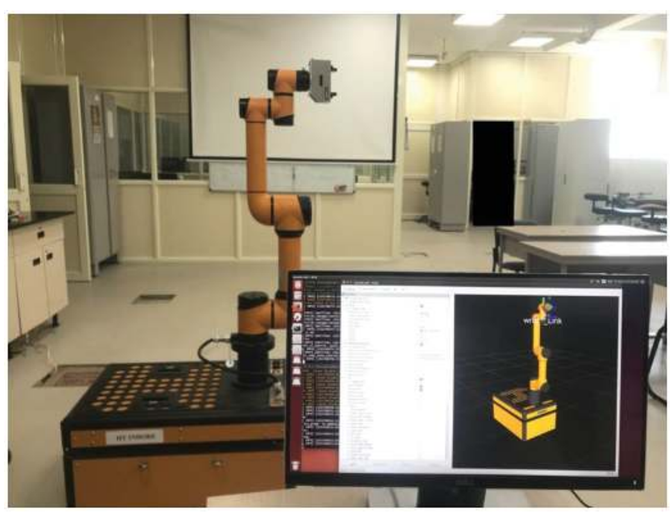

Figure 3. Real-time image of JR2 mobile manipulator in the MoveIt Software.

manipulator in the virtual background. Gazebo is a group of robot operating systems (ROS) packages provides a realistic simulation environment with obstacles and many other objects to test our robot in unknown conditions. Forward and inverse dynamic cases of the derived model are nearly identical with the virtual system motion.

The mobile manipulator will commence from its home position and bounded to track an eight-shaped spatial position trajectory as given in Figures 4 and 5. Figure 4 describes the desired spatial trajectory for the performance evaluation. Figure 5 displays the time trend of the given desired operational-space positions for the performance evaluation. For any mobile base systems, achieving a complex profile pattern as shown in Figure 4 is a very complicated and challenging task. Technical parameters of the JR2 mobile manipulator are described in Table 1. The proposed controller follows the given complex pattern successfully which is commonly used in industries for better reliability. Two different controllers are used namely a conventional backstepping and the proposed adaptive backstepping control for analysing the desired trajectory performance. The control laws can be stated as:

Conventional Backstepping Design:

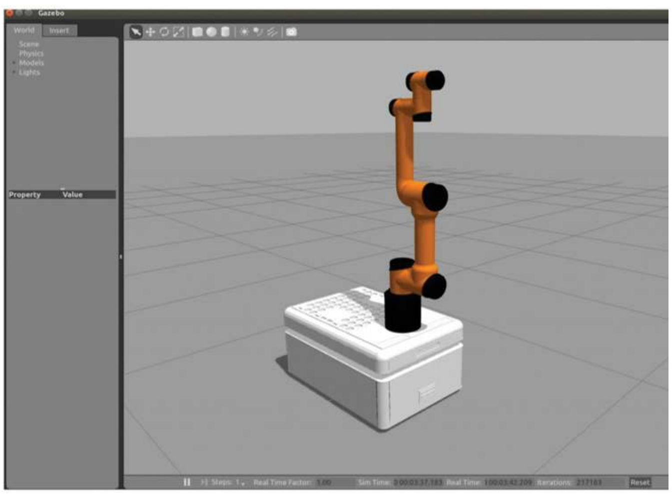

Figure 4. The JR2 mobile manipulator model in the Gazebo software.

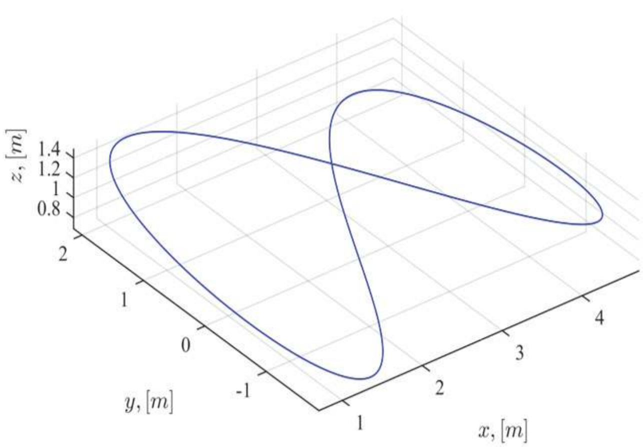

Figure 5. Desired complex spatial operational-space position trajectory for the performance evaluation.

$$\tau_{ct} = \hat{M}(x_1)\begin{pmatrix} J^{+}(x_1)(\ddot{x}_{1d} + K_1\dot{e}_1) + \dot{J}^{+}(x_1) \\ (\dot{x}_{1d} + K_1 e_1) + K_2 e_2 + J^{T}(x_1)e_1 \end{pmatrix} + \hat{\eta}(x_1, x_2) \quad (31)$$

Adaptive Backstepping Design:

$$\tau_{ct} = \hat{M}(x_1)\begin{pmatrix} J^{+}(x_1)(\ddot{x}_{1d} + K_1\dot{e}_1) + \dot{J}^{+}(x_1) \\ (\dot{x}_{1d} + K_1 e_1) + K_2 e_2 + J^{T}(x_1)e_1 \end{pmatrix} + \hat{\eta}(x_1, x_2) - \hat{\tau}_{dis} \quad (32)$$

4.2 Results and Discussions

The numerical simulation outcomes are attained based on the improved backstepping controller for a given spatial trajectory tracking and shown in Figures 7-9. The main aim is to gauge the effectiveness and feasibility of the designed control technique the simulations are carried out in the uncertain conditions. The uncertain conditions consist of ambiguities such as noises which are inserted in the simulation to dissect the behavior of the proposed scheme for the dynamic variations of the system. In the same way, the effect of external disturbances is believed as simple variations in payload (i.e., payload is changeable all through the preferred trajectory).

To have better comparison, the controller is tuned by genetic algorithm software in such a way that both controllers give an acceptable control performance under an ideal condition. There are two different working situations are taken into consideration for the numerical simulation analysis: an ideal working situation (it means that there are no external disturbances and uncertainties, no friction on road and joints) and working in uncertain situation. The ideal working situation is deliberated to illustrate that the conventional and the proposed performances in terms of gains and constants of the controller are approximately identical in terms of tracking feature and quantifiers. Figure 7 shows the time trend of the norm of operational-space position tracking errors at an ideal condition where both the controllers provide almost same results. $\tilde{\mu} = \mu_d - \mu$ is the operational-space pose error vector, defined as difference between desired operational-space pose

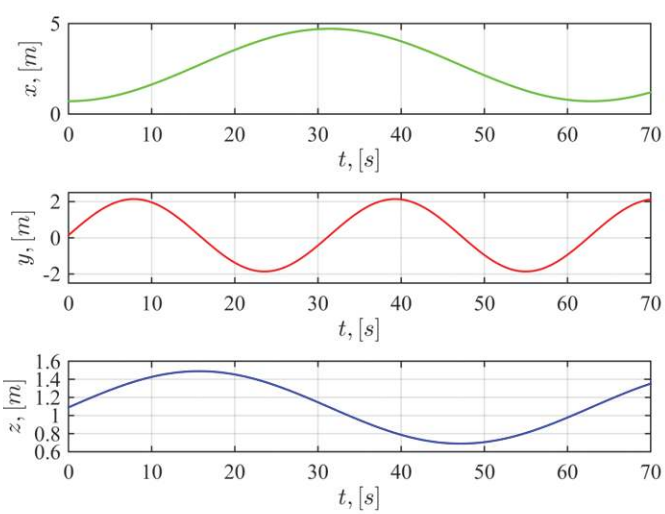

Figure 6. Desired operational-space positions time trajectories for the performance evaluation.

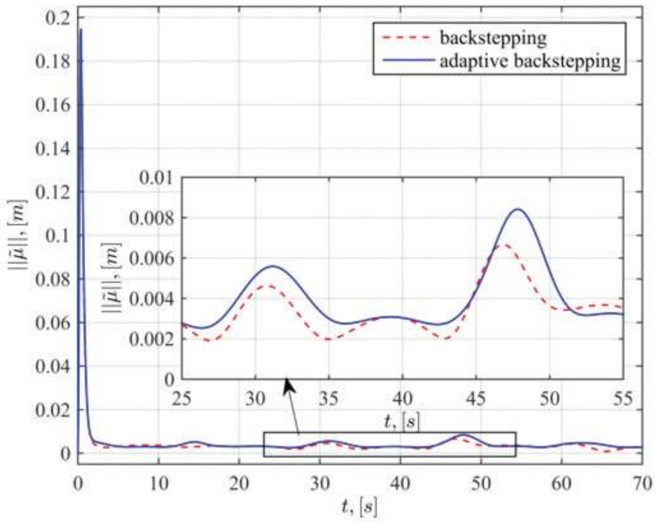

Figure 7. Operational-space position tracking errors at an ideal condition.

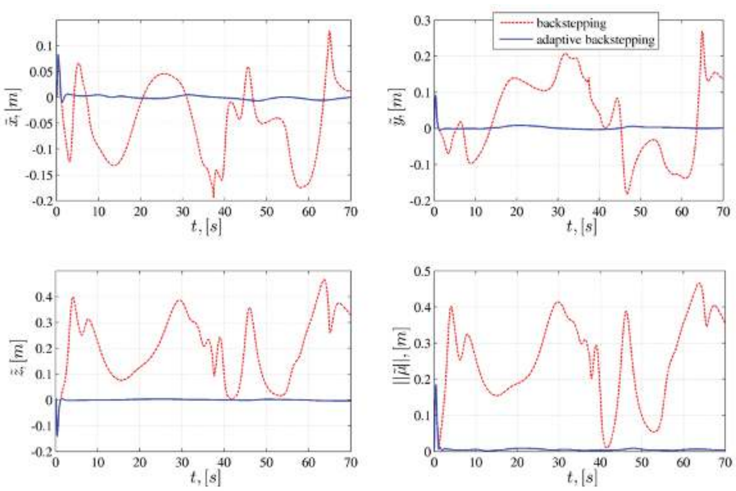

Figure 8. Operational-space position tracking errors at an uncertain condition.

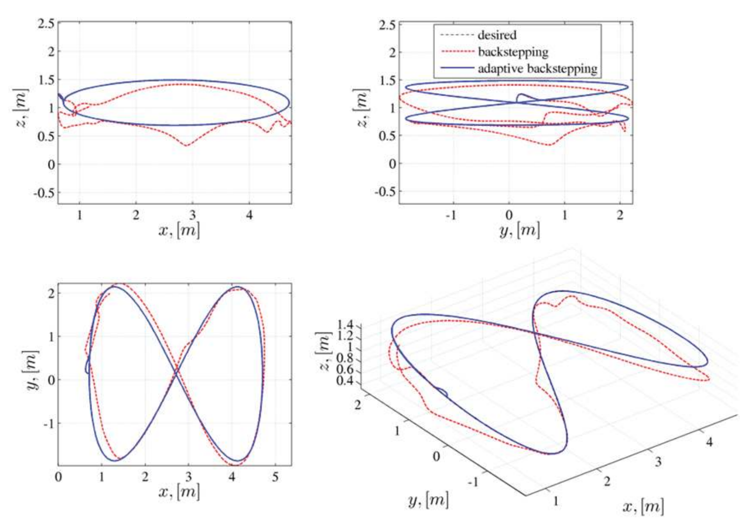

Figure 9. Comparative motion trajectories of the mobile manipulator during complex operational-space position trajectory tracking.

errors μ_d and actual operational space pose errors μ. In fact, the tuning has been done in such a way that the conventional control is performing well at the ideal conditions. From the results, it can be noticed that the proffered controller is initially has more tracking errors than the conventional control scheme. This is due to the inclusion of adaptive lawdepends on the disturbance observer. The disturbance observer is started with zero initial values of the arbitrary vector and there is 10% of system parameter uncertainties have considered for the ideal conditions.

In Figure.8, it represents the time histories norm of the operational-space position tracking errors at an uncertain situation showing x, y, z pose vectors. Both controllers are trying to follow the same classical test profile, however, the proposed controller over performs the conventional controller. The values of Euclidean norm (L_2 norm) of errors are presented to quantify the controller tracking performance. The comparative motion trajectories of the mobile manipulator during the complex operational-space position trajectory tracking are described in Figure 9. The controller parameters of the motion controller system used for the simulation are given in Table 2.

Table 2. Controller parameters

Controller Parameters	Values
$\mathbf{K}_1$	$4\,I_{3\times3}$
$\mathbf{K}_2$	$4\,I_{3\times3}$
$\mathbf{K}_3$	$4\,I_{3\times3}$
Uncertainty (%)	10

By conducting simulations for spatial operational-space trajectory in the vicinity of the system dynamic variations the controller parameter robustness is successfully verified. There are four different working parameters are used to demonstrate the system dynamic changes namely percentage of system uncertainties, payload, disturbance frequency and forward velocity of the system. Figure 10 shows the variation in the norm of tracking errors for system dynamic changes. The uncertainty in the system is varied from -20% to 20%, from no-load i.e. 0 kg to 3 kg maximum payload the unknown payload is varied. An external disturbance velocity is introduced in the controller apart from the uncertainty which varies from 0 to 1 rad/s and simulations has been performed to gauge the efficacy of the controller for fast fluctuating disturbances as well. It has been noted that when frequency and velocity of the system increase, the amplitude of the disturbances are also increase which gives the variation in the tracking errors norm. However, for the variations in payload and system uncertainties are not influencing the proposed controller much. Specifically, the recommended controller is robust enough to the system dynamic variations as long the disturbances are bounded or slowly varying. According to the numerical simulation results, under the variations caused by payload and uncertainties occurred due to parameters with slow changing external disturbances acting on the mobile manipulator, it has been observed that

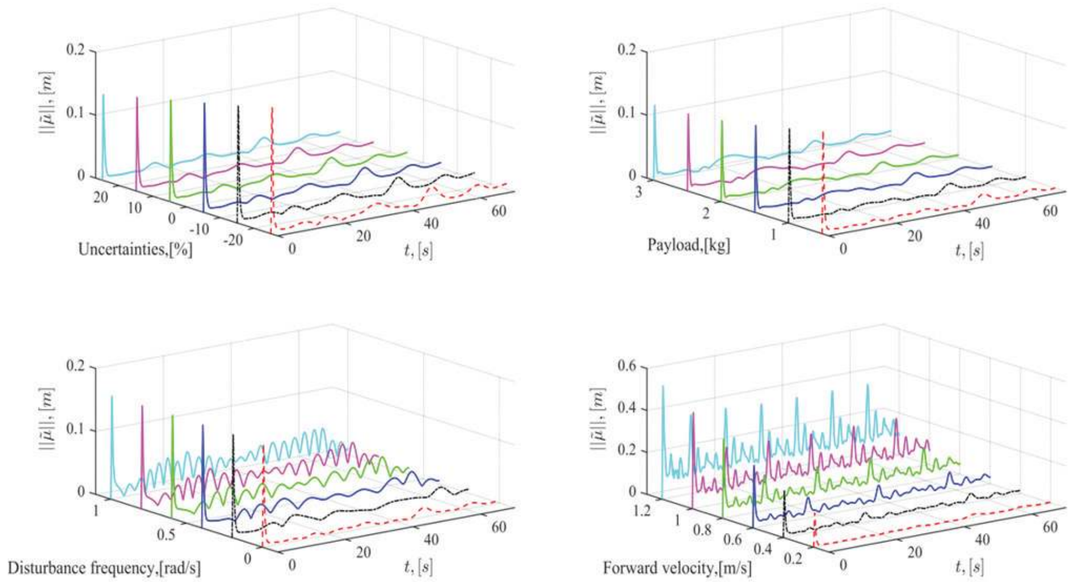

Figure 10. Time trend of the norm of operational-space position tracking errors under system dynamic variations (controller robustness results).

the recommended control scheme is robust in nature. Figure 11 Work flow diagrams among the parts of the JR2 mobile manipulator in actual operating conditions.

4.3 Real-Time Experiments and Discussions

In real-time experiments, an in-house fabricated mobile manipulator is considered for the performance analysis. The fabricated mobile manipulator subsists of 3DoFmobile base with four mecanum wheels attached with a 3DoF serial manipulator arm with rotary axes. In this in-house fabricated prototype, an Arduino mega as a low cost microcontroller, two dual dc motor drivers 20A and high torque encoder geared dc motor 12V 600rpmare used. Figure 12 shows in-house fabricated prototype attached with 2GB ram standard personal computer with Intel2.2 GHz processor along with 32bit operating system. In the real-time prototype {O} is the inertial frame, the mobile base frame is denoted by {B} and {T} is the wrist or tool frame. Fabricated prototype is also following the desired complex spatial operational-space position trajectory for performance evaluation. Table 3 shows the simulation parameters used for performance evaluation of the fabricated mobile manipulator.

Figure 13 demonstrates the schematic flow diagram among the components of the fabricated mobile manipulator in actual operating conditions. Figure 14 presents time histories of the norm of operational-space position tracking errors during real-time

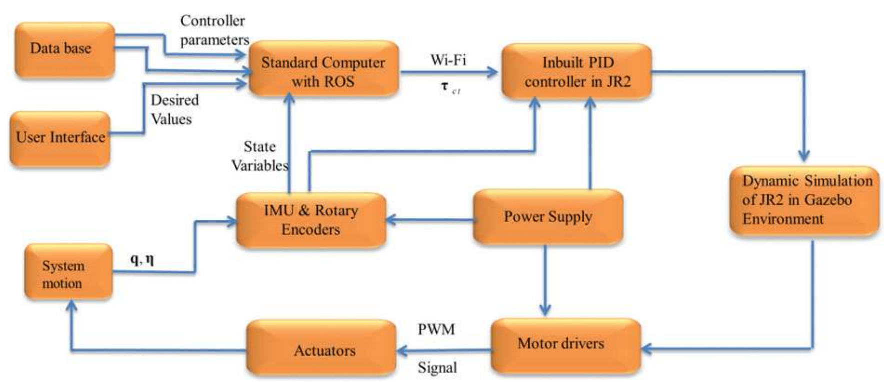

Figure 11. Work flow diagram among the parts of the JR2 mobile manipulator in actual operating conditions.

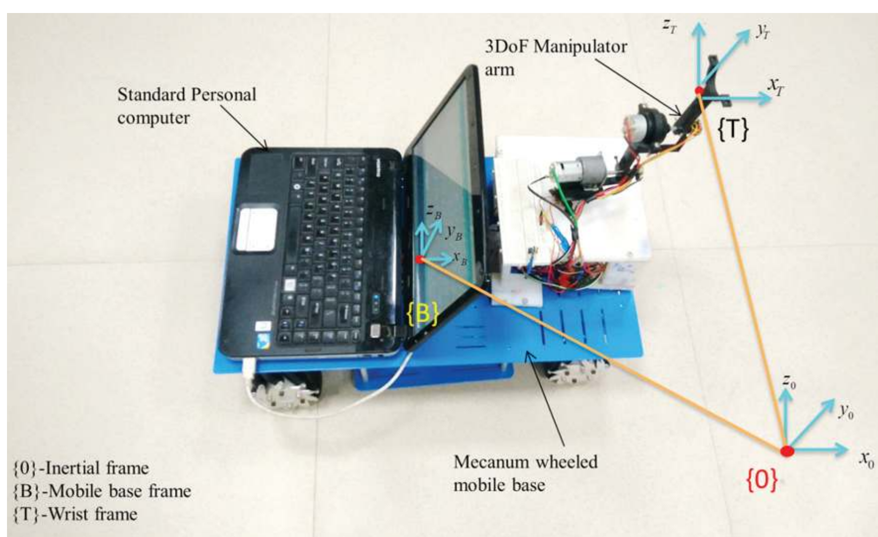

Figure 12. In-house fabricated prototype attached with the standard personal computer.

Table 3. Technical Parameters of the In-house Fabricated mobile manipulator

Parameters of Fabricated prototype	Values
Size of the mobile base	600mmX350mmX140mm
Maximum speed of the mobile base	1.04 m/s
Number of wheels	4
Number of manipulator axes	3
Work envelope of the manipulator	0.629 m^3
Horizontal distance between the vehicle frame to the manipulator base(L_v)	0.19 m
Vertical distance between the vehicle frame to the manipulator base (d_1)	0.16 m
Vehicle frame from the ground (height) (d_v)	0.136 m
Joint distance of the manipulator's second frame (d_2)	0
Joint distance of the manipulator's fourth frame (d_4)	0.09 m
Length of the manipulator second link (L_2)	0.105 m

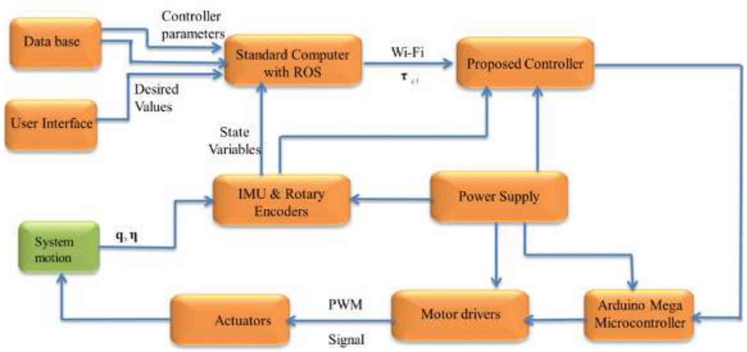

Figure 13. Schematic flow diagram among the components of the fabricated mobile manipulator in actual operating conditions.

tracking experiments on a fabricated prototype. It has been observed that adaptive backstepping shows better result than conventional backstepping in real-time prototype in the dynamic unknown environment.

The performance comparison of conventional and adaptive backstepping controllers between ideal and uncertain conditions are tabulated in terms of one of the popular error quantifiers namely integral of time absolute error (ITAE). Table 4 discusses the comparison of the controller performances in two different operating conditions i.e. in the ideal and uncertain conditions during operational-space tracking control.

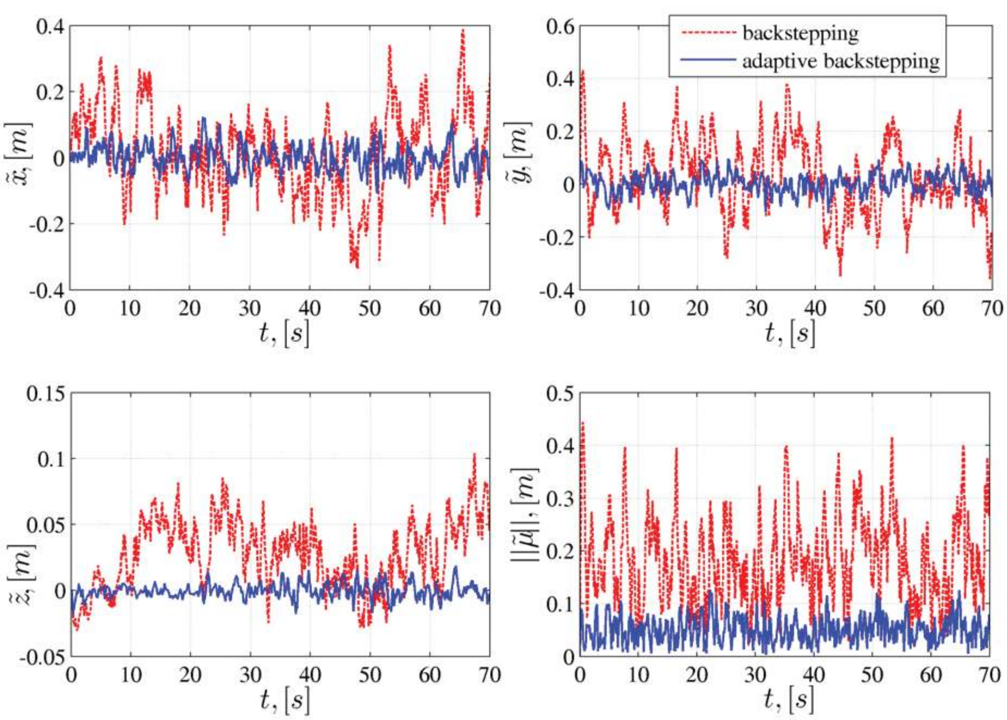

Figure 14. Operational-space position tracking errors during real-time tracking experiments on a fabricated prototype.

Table 4. Comparison of controller performances during operational-space position tracking at ideal and uncertain conditions

Condition	Scheme	Integral of Time Absolute Error (ITAE) in units		
		in x position	in y position	in z position
Ideal (Simulations on JR2)	Conventional Backstepping	4.488	5.088	0.285
	Adaptive Backstepping	6.077	5.598	1.111
Uncertain (Simulations on JR2)	Conventional Backstepping	175.973	263.363	533.406
	Adaptive Backstepping	6.352	5.997	3.977
Real-time Experiments (on a fabricated prototype)	Conventional Backstepping	279.138	272.087	87.854
	Adaptive Backstepping	76.023	77.656	8.375

5. CONCLUSIONS

This paper presents a comparative analysis of conventional and robust nonlinear adaptive backstepping control method for the desired operational-space motion control of a simple spatial 6-dof wheel based vehicle-manipulator system. The proposed controllers' viability is investigated under ideal and uncertain operating conditions. The control performance of the two motion control schemes is almost same and acceptable. The main intention in this motion control system is to track the operational-space position and performance of kinematic redundant mobile manipulator so that the tracking error congregates to zero. Global asymptotic stability and asymptotic tracking performance has been proved by the resultant proposed control law. The tracking performance shown under parametric uncertainty, nonlinear variations and uncertain friction property are stable. The system response is uniformly ultimately bounded which implies practical stability under Assumption 2 in Section 3. Comparison of controller performances has done with integral time of absolute errors at ideal and uncertain conditions also have been calculated in the XYZ positions. The results indisputably are a sign of the reduction in error accumulation. Hence the prospective controller's potency is demonstrated and established using simulations in Gazebo software for the mobile manipulator and investigations of the motion behavior. Real-time experimental results also proves that the adaptive backstepping control scheme gives improved results and follows the desired predefined complex spatial trajectory.

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