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Robust Trajectory Tracking Control of a Mobile Manipulator using Non-singular Terminal - Sliding Mode Control

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***Abstract:** In this work, a robust trajectory tracking control method is recommended and utilized for a kinematically inessential position tracking of mobile manipulator, in its task space in presence of parameter uncertainties and external disturbances. The suggested mobile manipulator consist 4 degrees-of-freedom (D-O-F) serial manipulator, which mounted on 3 D-O-F mobile bases. Using design of a terminal (NTSMC) non-singular sliding mode control for whole non-linear prototype of a mobile manipulator a robust tracking control is attained. This control arrangement convinces systems states finite time convergence because of added term which is non-linear in linear sliding surface which reflect in non-linear sliding mode known as terminal sliding mode (TSM). Furthermore, traditional terminal sliding mode control (TSMC) has a problem of singularity associated with it, overcome by the offered control scheme. The usefulness, feasibleness and robustness of suggested techniques are illustrated with the help of simulations (computer-based).*

***Keywords:** Mobile manipulator, Non-singularity, Terminal sliding mode (T-S-M)control.*

I. INTRODUCTION

In order to maximize reliable and fast tracking performance of the robot, robust fast tolerant adaptive control has been proposed. It gives high robustness, fast transient response and finite time convergence technique [29]. Back stepping control strategy approach is developed for current tracking control scheme to avoid problem of singularity point [34]. In [31] the authors have suggested APF-based path planning combined with a FAGNTSMC based tracking control mechanism for a team of mobile robots in master-slave form. The authors have proposed an adaptive stable and fast control method for controlling n-DOF robotic manipulator [30].The NTSMC is suggested and applied to a 4 linked non-linear SCARA robot manipulator in presence of uncertainties [33].

Over the years, the mobile manipulators have been utilized in successful manner for performing interactive and effective practical tasks such as laser cutting and drilling operations, pick and relocation of an object, arc welding or complex surface painting, peg-hole insertion, etc. [1,2]. The problem of singularity and collision avoidance enforcement is identified on the basis of an external penalty function method, which results in continuous and bounded mobile manipulator controls even close to boundaries of disturbance. The random profile methodology is used in [2] to cope with the mobile manipulator movement in order to execute a pick-up task. This is due to large work-space area and high mobility given by mobile manipulator in comparison with fixed base-manipulator. The communicative actions performance stability and high precision by controlling mobile manipulator in their task space.

Hence, primary aim of design of controller is to move mobile-manipulator from its initial arbitrary location to an aspired end-effector position expressed with fair accuracy in the coordinates of the task space [3]. Yet, for good tracking performance the development of control algorithms is a challenging task because of indeterminate state of dynamic model of the mobile manipulator. Principally including basic uncertain dynamic equations and state imbalance restrictions imposed on movement of mobile manipulator [1]. The structural uncertainty originated as a result of unidentified payload apprehended by end effector though the state inequality restrictions originated in work space due to presence of (unknown) obstacles. So that parametric uncertainties lies in kinematic and dynamic equations of mobile-manipulator. Moreover, mobile manipulator owns strong-coupled dynamics of manipulator and mobile-platforms. Therefore for such uncertain systems the design of control system turns curious topic of current research.Meanwhile, researchers have come up with control procedures for tracking control of mobile manipulators which is given in the literature. Including non-linear closed loop control [4, 35-39], Robust fault tolerant adaptive Control [29],task-null-space de-coupling-control [5], computed-torque control [6], neural-network-control [7-10],

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The fuzzy-logic control has the low response time because of complex computation[31], adaptive and robust tracking control consisting different blend of sliding-mode control ,neural-network and fuzzy, etc. [11-17]. Above mentioned research works have suggested a dynamic-control-law which includes summing up several procedures for controlling such as sliding-mode, back-stepping, neural network and fuzzy logic making design of controller more computationally expensive and gruelling. Furthermore, controllers from [3,20,21] pseudo-inverse and some controllers [4,18,19] require Jacobian-matrix inverse, respectively, which may results in mathematical Instabilities within a singular region. The inverse kinematic problem can be solved with a general algorithm of Jacobian pseudo-inverse given in autogenous configuration space [22].

Among aforesaid control methods, SMC consist of conventional sliding mode (CSM) and terminal sliding mode(TSM). The CSM is asymptotically stable and TSM is finite time stable [32]. The SMC which is continuous may assure systems asymptotic stability in the mode it indicates that for finite settling time the system states will converge to the equilibrium point. So as to confirm the finite time convergence, terminal sliding mode (TSM) known as sliding mode has been non-linear and projected as per concept of terminal attractor [23,24]. TSM provide fast and finite time convergence as compared to conventional SMC and advantageous for control with high precision [25]. Still, the present TSM controller design procedures have drawback of singularity [25]. Significant study has been finished to neglect the issue of singularity through (NTSMC) non-singular terminal sliding mode control. [25-28].

The SMC design includes two stages: stage one is to choose sliding mode surface, stage second is to design the sliding mode controller to guarantee the sliding mode existence so as to drive the system to get to sliding mode surface in finite time and thereafter remain on it. Here, trajectory tracking control design based on NTSMC is offered and is applied for a whole non-linear model of a mobile manipulator. External disturbances effects like sensor (used for measurement) parameter uncertainties and noises are incorporated into this dynamical model of a mobile manipulator. Finite time convergence property of work proposed is illustrated using Lyapunov based stability analysis. Numerical simulation on said manipulator system is performed to authenticate the efficacy of suggested technique.

II. PROPOSED METHODOLOGY

In Proposed work, mentioned mobile-manipulator encompass a 4- wheeled mobile-platform mounted with 4-link manipulator. Four motors in wheel drives manipulator base independently. Design as per concept of the proposed mobile manipulator is portrayed in Fig.1, where, Earth-fixed (inertial) frame is I(0; 0; 0), mobile base (moving) frame is M(x; y; z) and end-effector frame is T(x_t ; y_t ; z_t).Newton-Euler method given below can be used to develop equation of Dynamic-motion of mobile manipulator:

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

where, vector of confi-guration (joint) position-variables is $q \in \Re^{7\times1}$ in addition the vector of mobile-base positions is $q = [\zeta \quad \xi]^T, \zeta \in \Re^{3\times1}$ and vector of manipulator joint positions is $\zeta=[x\ y\ \gamma]^T$; $\xi \in \Re^{4\times1}$ and $\xi = [d_1\ \theta_2\ \theta_3\ \theta_4]^T$; x , y and γ represents mobile base translation-positions and yaw-angular displacement. d_1, θ_2, θ_3 and θ_4 are the manipulator joint displacement-angles of analogous mobile-manipulator links. Vector of inertial forces plus manipulator moments is $M(q)\ddot{q}$, Effects of Coriolis and centripetal vector for manipulator:

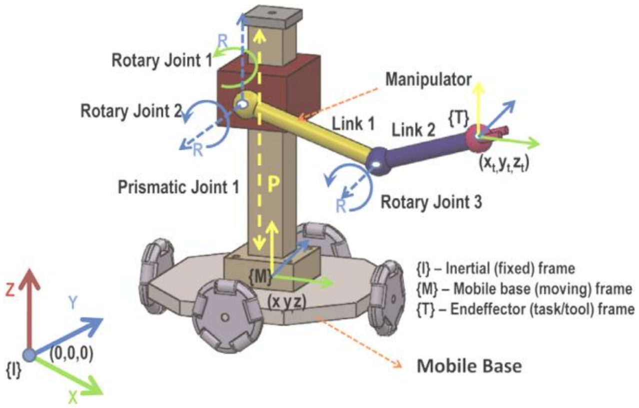

Fig. 1 Proposed Conceptual design for mobile manipulator

$C(q,\dot{q})\dot{q}$, Gravity-effects vector of manipulator: g(q), f_{dis} is the system-including lumped disturbance vector frictional effects, uncertainties and external disturbances. Vector of control input torques is $\tau=[\tau_m \quad \tau_b]^T \in \Re^{7\times1}$, where Input torques vector is $\tau_m \in \Re^{4\times1}$ implied for serial manipulator control fixed on mobile manipulator and $\tau_b \in \Re^{3\times1}$ is Input-torques vector to control mobile manipulator base. The lumped-disturbance vector (f_{dis}) is given by

$$f_{dis} = f_{idis} + f_{edis} \quad (2)$$

where, External-disturbances vector acting on mobile manipulator : f_{edis} . Vector of internal disturbances f_{idis} because of para-metric un-certainties and disturbances caused because of measurement noises and may be expressed as-

$$f_{idis} = \Delta M(q)\ddot{q} + \Delta C(q,\dot{q})\dot{q} + \Delta g(q) + F(q,\dot{q})\dot{q} + \nu \quad (3)$$

Where $\Delta M(q)\ddot{q}$, $\Delta C(q,\dot{q})\dot{q}$ and $\Delta g(q)$ are the parameter un-certainties in the $M(q)\ddot{q}$,$C(q,\dot{q})\dot{q}$ and g(q) respectively. $F(q,\dot{q})\dot{q}$ Vector represents effects of friction (Coulomb, viscous and static) because of manipulator-joint. Vector "ν " indicates internal disturbances introduced by position-velocity measurement devices. The properties of a mobile manipulator system held with earth-fixed vector representation for system dynamics. Which is finite-dimensional are given below.

Property1. The inertia matrix M(q) is positive definite and symmetric(PDS) i.e.

$$M(q) = M^T(q) > 0, \forall q \in \Re \quad (4)$$

There occurs a non-negative constants m_m in addition m_M i.e. $m_m \leq \|M(q)\| \leq m_M$

Property2. The matrix $M(q)\ddot{q} - 2C(q,\dot{q})\dot{q}$ is a skew symmetric matrix i.e.

$$s^T[M(q) - 2C(q,\dot{q})]s = 0, \forall s \in \Re, q \in \Re \quad (5)$$

The block diagram of the proposed methodology has shown in fig.2.

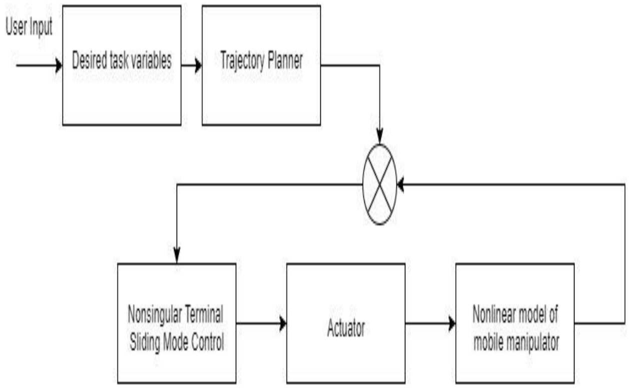

Fig. 2 Block diagram of the proposed control system

III. CONTROL DESIGN ALGORITHM

The objective of this control is to track the set point position q_d by forcing the states q. Tracking error can be defined as,

$$e = q_d - q \qquad (6)$$

where, q_d represents desired trajectory. For the system (1) definition of a terminal siding surface which is non-singular can be [25],[27] .

$$s(t) = e(t) + \frac{1}{\beta}\dot{e}(t)^{\frac{p}{q}} = 0 \qquad (7)$$

Where $\beta = diag[\beta_1, \ldots, \beta_i, \ldots, \beta_n]$ in which β_i is a positive constant, non-negative odd integers are p and q, which fulfil the condition as below:

$$p > q \qquad (8)$$

Condition for sufficiency to show presence of terminal sliding mode is given as

$$\frac{1}{2}\frac{d}{dt}s_i(t)^2 < -\zeta_i|s_i(t)| \qquad (9)$$

Where $\zeta_i (i = 1, \ldots, n)$ is a positive constant. When the terminal sliding mode is as shown in system "(1)" i.e. $s_n(t) = 0$, now by using non-linear differential equation its dynamics obtained as shown below:

$$-\dot{e}(t)^{\frac{p}{q}} = \beta e(t) \qquad (10)$$

e(t) approach terminal sliding surface s(t) = 0 infinite period of time $t_{r_i}(i = 1, \ldots, n)$, as $s(t) \neq 0$, which fulfills

$$t_{r_i} \leq \frac{|s_i(0)|}{\zeta_i} \qquad (11)$$

Assuming NTSMC as shown with (7),sufficient condition as shown by "(9)", and the mobile manipulator scheme is stable when NTSMC control law preferred as,

$$\tau = M(q)\left(\ddot{q}_d + \beta\frac{q}{p}\dot{e}(t)^{2-\frac{p}{q}} + \zeta sgn(s)\right) + C(q,\dot{q})\dot{q} + g(q) \qquad (12)$$

A function which is discontinuous $sgn(s)$ given in "(12)" will gives chattering of control input. Hence it may causes wear and tear to the manipulator systems actuators. Discontinuous function $sgn(s)$ is interchanged with saturation function which is continuous $sat(s,\phi)$, to overcome above undesirable control chattering, same is defined as :

$$\{sat(s,\phi)\}_i = \begin{cases} \frac{s_i}{|s_i|} & if \quad s_i > \phi_i \\ \frac{s_i}{\phi_i} & if \quad s_i \leq \phi_i \end{cases} \qquad (13)$$

Where ϕ_i is thickness of boundary layer.

IV. STABILITY ANALYSIS

Now, to demonstrate the convergence property of the planned NTSMC controller, 'Lyapunov stability analysis' method is helpful. To illustrate the stability analysis of present suggested NTSMC controller, assumptions made, can be as shown below.

Assumption1. The term known as lumped disturbance f_{dis} is bounded also it consists of a constant $F_{max} > 0$ such that $0 \leq |f_{dis}| \leq F_{max}$

Assumption2. The states q and $\dot{q}$ are obtainable to measure measurand.

Assumption3. The required trajectory, q_d is double differential as well as smooth i.e. q_d, $\dot{q}_d$, $\ddot{q}_d$ and obtainable through well-known limits.

Theorem1. Assume dynamics of a mobile manipulator in "(1)" with properties in "(4)-(5)". When control input vector is chosen as per definition given in "(12)", error vector which is tracking the output, converges to zero infinite period of time with respect to s.

Proof Assume function known as Lyapnunov candidate as

$$V = \frac{1}{2}s^T M s \qquad (14)$$

Taking derivative of V from "(14)", it becomes,

$$\dot{V} = \frac{1}{2}\{\dot{s}^T M s + s^T \dot{M} s + s^T M \dot{s}\} \qquad (15)$$

Since $s^T M \dot{s} = \dot{s}^T M s$, $\dot{M}$=2C(q,$\dot{q}$)(Property2) can be solved as

$$\dot{V} = s^T\{M\dot{s} + C(q,\dot{q})s\} \qquad (16)$$

$$\dot{V} = s^T\{M\left(\dot{e}(t) + \frac{1}{\beta}\frac{p}{q}diag\left(\dot{e}(t)^{\frac{p}{q}-1}\right)\ddot{e}(t)\right) + C(q,\dot{q})s\} \qquad (17)$$

Now

$$\ddot{e}(t) = \ddot{q}_d - \ddot{q} \qquad (18)$$

As given in equation (1) as well as "(12)", it gives,

$$\ddot{e}(t) = -\beta\frac{q}{p}diag(\dot{e}(t)^{2-\frac{p}{q}}) - \zeta sgn(s) - M^{-1}f_{dis} \qquad (19)$$

Substituting value of $\ddot{e}(t)$ to "(17)" through "(19)" it Becomes

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Table 1: Performance Indices of controllers

Control Schemes	$\tilde{\mu}_x$			$\tilde{\mu}_y$			$\tilde{\mu}_z$		
	RMS	IAE	ITAE	RMS	IAE	ITAE	RMS	IAE	ITAE
LPID	0.0675	55.5897	24839	0.0574	51.6067	26985	0.0586	51.9647	24824
CTC	0.0286	21.6217	9371.9	0.022	19.9124	10362	0.0245	20.5275	9382.7
NTSMC	0.0019	0.3511	78.8374	0.00052	0.1646	72.6711	0.0029	0.6718	313.3997

$$\dot{V} \leq s^T \left\{\frac{1}{\beta}\frac{p}{q} diag\left(\dot{e}(t)^{\frac{p}{q}-1}\right)[-M\zeta sgn(s) - f_{dis}]\right\} + s^T C(q,\dot{q})^T s \quad (20)$$

As p, q are positive-odd-integers and $1 < \frac{p}{q} < 2$, there is $\dot{e}(t)^{\frac{p}{q}-1} > 0$for $\dot{e}_i \neq 0$. So, Lyapunov function time derivative is negative definite if

$$|\zeta_i| > |\tau_{dis_i}| \quad (21)$$

Thus as per "(21)" the Lyapunov function V satisfies following type of differential inequality

$$\dot{V}(t) \leq -V(t)^{\alpha}\gamma \quad (22)$$

It consist, $\alpha\epsilon(0,1)$ plus $\gamma > 0$. Henceforth, infinite time a non-singular non-linear sliding surface given in "(7)" as per Lyapunov stability standards converges to zero.

V. RESULT ANALYSIS

A. Explanation of the proposed system

To illustrate the potential of control technique on given robotic-system, in depth computer-based simulations were conducted. Above mentioned system comprises of 4-D-O-F (P-R-R-R) serial-manipulator mounted on 3-D-O-F mobile-base. The test case is preferred in such a way that movement of manipulator starts at initial position, returning back to initial-position after traveling a set complex targeted path. When the task was being conducted, an object of indefinite mass was picked by manipulator at original position (for e.g., pay-load of 2 kg taken into consideration for simulation), transfer this unidentified mass of load near its predetermined pathway and place object on targeted point of position.

B. Simulation results and discussions

In this section, outputs obtained from computer based simulation for task space trajectory shown above, which is represented in Figs. 2-4.

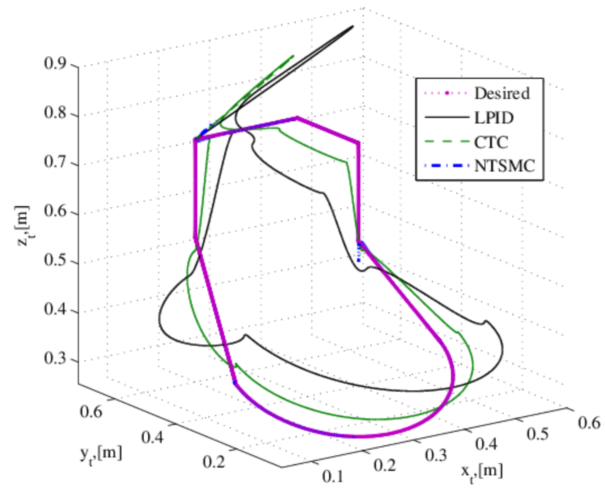

Fig. 2 3D view of TTC (trajectory tracking control) with indefinite condition

The variation in pay-load is starting zero kg (No-load) to 2.5 kg (full-pay-load). Along with this, the system uncertainty varies (-40 % to 40 %), robustness of controller has also been certified. To have a proper understanding of the robustness of system, an external-disturbance-vector in addition to system un-certainty is included and is shown by

$$\delta_{dis} = \begin{bmatrix} 5\cos(w_d t) \\ 5\sin(w_d t) \\ 5\cos(w_d t) \end{bmatrix} in\ N \quad (23)$$

Where, " w_d" external disturbance frequency, changes (0-2 rad/s) and carries out simulations to determine controller performance in case of rapid changing disturbances. To show validity of proposed technique, the relative study has been carried out with renowned controllers alike computed torque controller (CTC) and linear Proportional-Integral-Derivative (LPID) controller. Control laws of mentioned controllers can be expressed as:

$$\eta = K_p\tilde{u} + K_I \int \tilde{u}dt + K_D \frac{d\tilde{u}}{dt} : \qquad \text{PID}$$

$$\eta = \hat{M}(\mu)\left(\ddot{\mu}_d + K_1\dot{\tilde{u}} + K_2\tilde{u}\right) + \hat{C}(\mu,\dot{\mu})\dot{\mu} + \hat{g}(\mu): \qquad \text{CTC}$$

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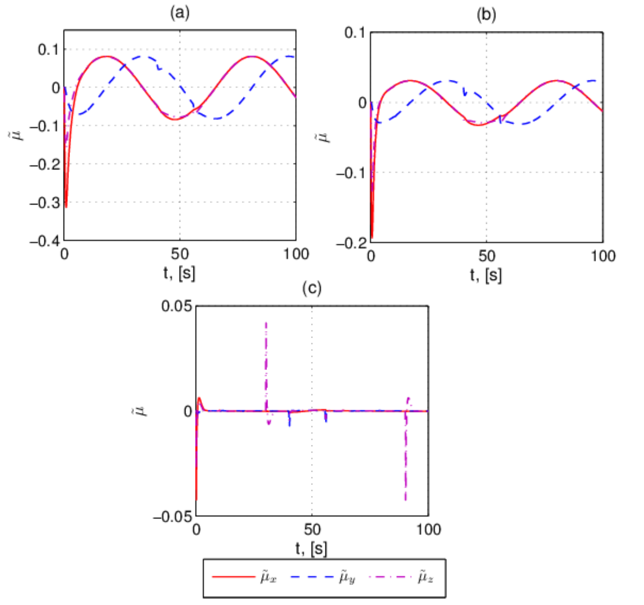

Fig.3 3D view of TTC (Trajectory tracking control) with indefinite condition

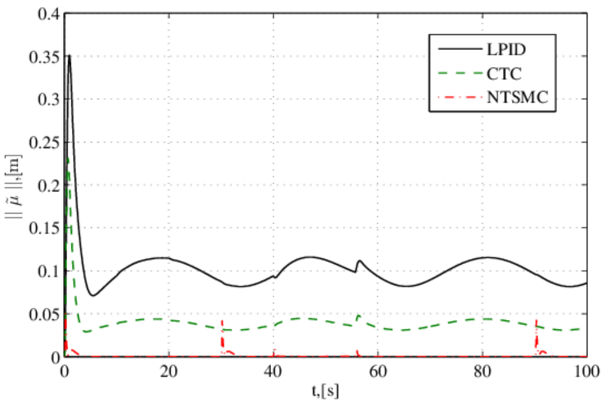

Fig.4. The change in tracking position norm deviations throughout complex-task-space trajectory tracking-control with indeterminate situation

In order to achieve a better comparison, controller gain matrices are set in correspondence that all controllers give satisfactory control performance in exemplary conditions $(i.e. f_{dis} = 0)$ and just about same in terms of tracking errors. LPID parameters for favourable controller are, KP = 6:5, KI = 3:5, KD = 1:25; for CTC, K1 = 4:56, K2 = 6:32,
For proposed NTSMC: p = 5, q = 3, β = 8, ζ= 15 and φ= 0:009.

Fig. 3 displays the relative outcome of controllers in case of Tracking of complex-task-space location along with indefinite condition. As per outcome, we may conclude that the controller effectively follows the required complex path and carries out relocating of an object simultaneously.

The L-P-I-D and C-T-C methods give considerable errors at the time of trajectory tracking and insufficient in managing parameter uncertainties and external disturbances. We established this by observing task space time histories errors given by these controllers and is shown in Fig.4. Tracking-error-norm times-trajectories (Eu-clidean norm) are shown in Fig. 4 and justifies the pitched scheme performance. A quantitative analysis of the tracking performance of a mobile manipulator given by all the controllers in terms of root mean square of the error (RMS), integral of the absolute-error (I-A-E) and integral of the time-absolute-Error (I-T-A-E) is done and shown in Table 1. It is confirmed from this table that the projected control pattern gives less tracking faults in the x, y and z directions compared to other controllers.

VI. COLCLUSION

A non-linear non-singular robust *T-S-M* control method offered as well as applied for composite preordained task space motion control of a 7 D-O-F mobile manipulator system. Effectiveness of the suggested method has been certified by comparing its performance with existing controllers. Simulation results confirms that the suggested technique outperforms well in terms of robustness, tracking and finite time error convergence.

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