Adaptive Control of Mobile Manipulator Robot based on Virtual Decomposition Approach

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Abstract: This paper presents an adaptive control scheme for a mobile manipulator robot based on the virtual decomposition control (VDC). The control strategy was tested on three degrees of freedom manipulator arm mounted on two degrees of freedom mobile platform to track a desired trajectory. The desired trajectory is obtained from the workspace trajectory using the inverse kinematics. Differently to the known decentralized control that divides the mobile manipulator into two subsystems, in this paper, the mobile manipulator has N degrees of freedom, divided virtually into N subsystems. The applicability of the proposed scheme is demonstrated in real time validation. The experimental results show the effectiveness of the VDC approach.

1 INTRODUCTION

The need for robots capable of locomotion and manipulation has led to the design of mobile manipulator robot (MMR) platforms. A mobile manipulator is a robotic manipulator arm mounted on a mobile platform. Typical examples of MMR include satellite arms, underwater robots in seabed exploration and vehicles used in extra-planetary exploration. The mobile manipulator comprises two subsystems, that is, the mobile platform and the manipulator arm subsystem. However, this significantly complicates the robotic system as its control design complexity increases greatly. The problem of controlling the mechanical system lies in the fact that it imposes a set of kinematic constraints on the coordination of the position and velocity of the mobile manipulator. Few works have been proposed to solve the control problem of these robotic systems, which have high degrees of freedom and are tightly interconnected.

In the recent years, the research in the design, control, stability, and path tracking of mobile manipulators have significantly increased. Most of these studies have thus far focused on the tracking control of mobile manipulators. Two main schemes of control are developed in the literature: The first one is centralized control, in which the mobile manipulator is regarded as one system and the controller is designed for the full system. The second one is the decentralized control, in which controllers for two subsystems are designed separately and no coupling is considered. In the first approach, where the mobile platform and the manipulator arm are regarded as a complete system, many control approaches were developed and implemented. In (Yamamoto and Yun 1994), the authors focused on the interaction between the manipulator arm and the mobile platform. A nonlinear feedback control was developed to compensate the dynamic interaction. Studies discussing the problem of modeling and control of mobile manipulator were given in (Chung and Velinsky 1998, Seraji 1998, Song et al. 2005, Aviles et al. 2012, Galicki 2012), where the robotics system is considered as a complete system. Many other works have used decentralized control for this type of robotic systems as in (Tan and Xi 2001, Ngo et al. 2007, Ge et al. 2008, Chen et al. 2015) where the manipulator arm and the mobile platform are viewed as two separated subsystems. LQR controller for mobile manipulator was proposed (Chen et al. 2015), where the manipulator arm and the mobile

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platform are controlled independently. In (Ge et al. 2008) a sliding mode control was proposed to control the mobile platform and a nonsingular terminal sliding mode control for the manipulator's arm.

Conventional control approaches consider integrated mobile manipulator dynamics. However, in practice, it becomes very difficult to get the exact model and uncertainties may still exist. In (Wu and Sun 2014) an adaptive tracking control scheme was proposed for a mobile manipulator with the presence of uncertainties and disturbance based on suitable reduced dynamic model. An adaptive sliding mode controller based on the backstepping applied to the trajectory tracking of the wheeled mobile manipulator was introduced in (Chen et al. 2013). An adaptive control scheme based on suitable reduced dynamic model was proposed in (Dong 2002), without considering any disturbance. To overcome the problem of dynamic modeling and dynamic control, some researchers proposed adaptive control based on neural network control and fuzzy logic approaches. For instance, non-model-based techniques have been developed for a different type of mobile manipulator robot with dynamic parameters uncertainties (Mai and Wang 2014, Peng et al. 2014, Wu et al. 2014).

A. Main Contribution

All previous studies based on Lagrangian or Newton/Euler approaches require knowledge of the exact parameters of the system. In practice, this is difficult, and the obtained model is usually uncertain. For these types of systems with large degrees of freedom, and which are tightly coupled, adapting the parameters using methods based on full dynamics is very complicated due to the huge number of parameters involved.

To overcome, this problem we propose in this paper a novel adaptive decentralized approach based on an extension of the virtual decomposition control (VDC) methodology in (Zhu 2010, Brahmi et al. 2013) originally designed for fixed-base robotic systems with large degrees of freedom. Some of the many advantages of this approach are: 1) the whole dynamics of the system can be easily found based on the individual dynamics of each subsystem; 2) the control only uses subsystem dynamics while guaranteeing the stability of the entire system; and 3) it makes the adaptation of the physical parameters very simple and systematic.

In opposite to known decentralized control techniques that divide the mobile manipulator into two subsystems, in our work, if the mobile manipulator that has N degrees of freedom then the robotics system is divided virtually into N subsystems. This simplifies the control and the dynamic parameters adaptation.

The rest of the paper is organized as follows. Section 2 presents the modeling of the system while section 3 presents the control problem statement. Section 4 explains the control design and experimental results are given in section 5. Finally, a conclusion is given in section 6.

2 MODELING AND SYSTEM DESCRIPTION

Before Before giving the rationale behind the virtual decomposition approach, we start by giving a brief formulation of the kinematic and dynamic modeling of the mobile manipulator robot under consideration. Figure 1 shows the holonomic manipulator arm mounted on nonholonomic mobile platform, where the manipulator has ***p***-DOF, the mobile platform has ***m***-DOF and the full robotic system has ***n=m+p***-DOF.

Figure 1 shows the MMR with P_e being the position/orientation vector of the MMR end–effector.

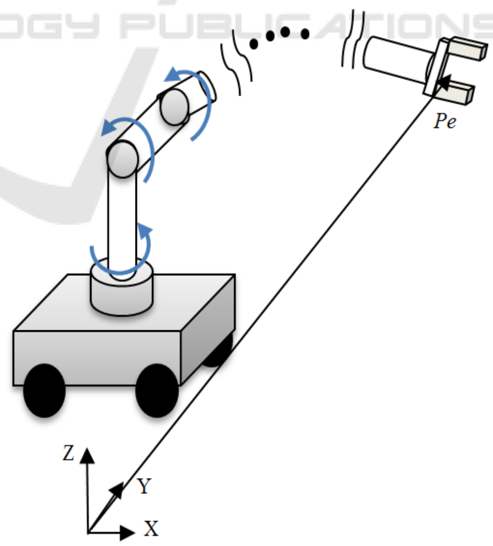

Figure 1: *n*- DOF mobile manipulator robot.

2.1 Kinematics

The relationship between the end effector velocity $V_e \in \mathbb{R}^6$ of the mobile manipulator and the linear/angular velocity of mobile platform $\dot{q}_v = \left[\dot{x}, \dot{y}, \dot{\theta}\right]^T$ and joints velocities of the manipulator arm $\dot{q}_a = [\dot{q}_1, .., \dot{q}_m]^T$ is given by:

$$V_e = J_e \dot{q} \quad (1)$$

where, $\dot{q} = [\dot{q}_v, \dot{q}_a]^T \in \mathbb{R}^n$ and $J_e \in \mathbb{R}^{6\times n}$ is the Jacobian matrix.

2.2 The Mobile Manipulator Dynamics

The dynamic model of the mobile manipulator developed using Lagrangian approach is given in the general joint space by the following equation:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \mathrm{E}\tau + A^T\lambda \quad (2)$$

where $M \in \mathbb{R}^{n\times n}$ is the mass matrix, $C \in \mathbb{R}^{n\times n}$ represents the Coriolis and centrifugal terms, $G \in \mathbb{R}^n$ is the vector of gravity, $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$ are the generalized coordinate vector, the joint velocity and the acceleration vectors respectively , $E \in \mathbb{R}^{n\times k}$ is a full rank transformation matrix and $\tau \in \mathbb{R}^k$ is the input control vector, $A \in \mathbb{R}^{r\times n}$ is the constraint matrix and $\lambda \in \mathbb{R}^r$ is the constraint force.

The mobile manipulator robot is considered as a fully actuated arm mounted on the nonholonomic mobile platform. This nonholonomic constraint is given as:

$$A(q)\dot{q} = 0 \quad (3)$$

The objective is to eliminate the term of constraint $A^T\lambda$, using the kinematic equations of the mobile platform and the right and the left wheels' angular velocities $\dot{q}_R$ and $\dot{q}_L$ that are obtained by the following expression:

$$\dot{q} = S(q)\dot{\eta} \quad (4)$$

where, $\dot{q} = [\dot{q}_v, \dot{q}_a]^T$ is the generalized coordinate linear/angular velocities, $S(q)$ is in the null space of the kinematic constraint matrix $A(q)$ and $\dot{\eta} = [\dot{q}_R, \dot{q}_L, \dot{q}_a]^T$ are the generalized coordinate angular right/left wheels velocities and the manipulator joint velocities. Therefore, we obtain:

$$S^T(q)A^T(q) = 0 \quad (5)$$

Based on (2), (4) and (5) the dynamic model (2) can be expressed by a linear relationship of the form:

$$\mathrm{H}(q)\ddot{\eta} + \mathrm{B}(q,\dot{q})\dot{\eta} + \Im(q) = W(q,\dot{q},\dot{\eta},\ddot{\eta})\Gamma = \tau \quad (6)$$

where $\mathrm{H}(q) = S^T M\, S$, $B(q) = S^T\left(M\dot{S} + C\,S\right)$, $\Im(q) = S^T G$ The physical parameters of the robot are unknown and had to be estimated. Using the estimate parameters of Γ, noted $\hat{\Gamma}$, the equation of parametrization expression can be written as:

$$\hat{\mathrm{H}}(q)\ddot{\eta} + \hat{\mathrm{B}}(q,\dot{q})\dot{\eta} + \hat{\Im}(q) = W(q,\dot{q},\dot{\eta},\ddot{\eta})\hat{\Gamma} \quad (7)$$

In the classical decentralized/centralized approach based adaptive control, it's very difficult to obtain these parameters when the degree of freedom increases. Usually, the size of the parameters vector Γ can be greater than 100 in this category of robots (Zhu 2010, Brahmi et al. 2013). As a solution of this serious problem, we use a novel adaptive control based on the virtual decomposition approach where the problem of control and adaptation of parameters are converted to each rigid body and each joint.

To simplify the control formulation, the following assumption is made:

Assumption 2.1: All the joints' velocities of the mobile manipulator robots are available for feedback.

The dynamics given in equation (6) has the following properties:

Property 2.1: the matrix H is symmetric positive definite.

Property 2.2: the matrix $Q = \dot{H} - 2B$ is skew symmetric, that is, for any vector x, we have: $x^T\left(\dot{H} - 2B\right)x = 0$

3 CONTROL PROBLEM STATEMENT

The idea of the VDC is to break down the robotic system into a graph consisting of several objects and open chains. An object is a rigid body and open chain consists of a series of rigid links connected one by one by a hinge and has a certain degree of freedom. The dynamic coupling between the subsystems can be represented by the flow of virtual power (FVP) at the cutting point. This refers to the principle of virtual work (Zhu 2010, Brahmi et al. 2013) and results in one open chain.

For the controller design, only the dynamics of the rigid bodies and the joints are required.

The control objective is to generate a set of torque inputs such that the joint position's tracking error converges asymptotically to zero. Formally speaking, the control problem is to design the control input:

$$\tau = f(q, \dot{q})$$

such that the following limits hold:

$$\lim_{t\to\infty}\|q-q_d\|=0,\ \lim_{t\to\infty}\|\dot{q}-\dot{q}_d\|=0$$

where, $q \in \mathbb{R}^n$, $q_d \in \mathbb{R}^n$ are the measured and desired joint angular position and velocity of the mobile manipulator.

4 CONTROL DESIGN

The overall control system is designed using the following steps:

- The joint space desired trajectories are obtained from the workspace desired trajectories using the inverse kinematics(1).
- The required joint space trajectory are computed from the desired trajectory in joint space.
- The required velocity $V_B^r \in \mathbb{R}^{6n}$ of the n body-fixed frames B_j illustrated in Figure 2. is calculated.
- The VDC approach is used to simplify the problem of adaptation of the parameters of the complete system, where this problem is converted into a problem of estimation of the parameters of each subsystem. From the velocities computed in the first step, the estimated parameters are calculated.
- The control law of the mobile manipulator robot is finally designed.

4.1 Design

Step 1: the desired joint velocity $\dot{q}_d \in \mathbb{R}^n$ is calculated based on (1), and then the required joint velocities are by $\dot{q}_r$

$$\dot{q}^r = \dot{q}_d + K_p(q_d - q) \tag{8}$$

with K_p is a positive gain matrix.

Step 2: In this step, the goal is to virtually decompose (Zhu 2010, Brahmi et al. 2013) the robotic system into several parts and open chain elements. Each part is a rigid body and open chain consists of a series of rigid links connected one by one. This decomposition is illustrated in Figure 2.

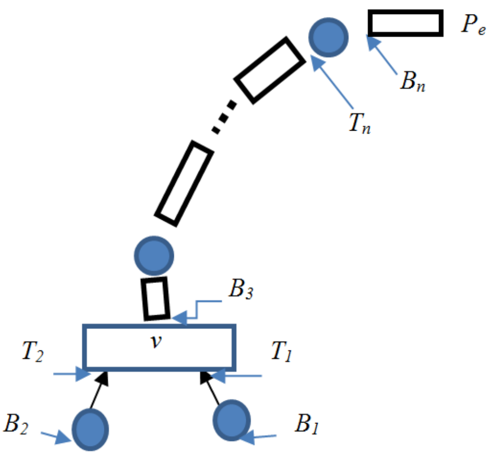

Figure 2: Virtual decomposition of the MMR.

In this step the linear/angular velocity vectors of each frame B_j is defined as: $V_B = \left[\dot{q}_1,...,\dot{q}_n, V_v, V_{B_1}^T,...,V_{B_n}^T\right]^T$ and is calculated as follows:

$$V_{B_{j+1}} = z\,\dot{q}_{j+1} + {}^{B_j}U_{B_{J+1}}^T V_{B_j} \tag{9}$$

where, $\dot{q}_j$ is the joint velocity, $V_{B_j} \in \mathbb{R}^6$ the linear and angular velocity of the corresponding frame, $V_v \in \mathbb{R}^6$ is the velocity of the mobile platform and z is defined as $z = [0\ 0\ 1\ 0\ 0\ 0]^T$ for prismatic axes and as $z = [0\ 0\ 0\ 0\ 0\ 1]^T$ for revolute axes.

The transformation matrix of force/moment vectors from frame B to frame A is defined by:

$${}^A U_B = \begin{bmatrix} {}^A R_B & 0_{3\times3} \\ S\left({}^A r_{AB}\right){}^A R_B & {}^A R_B \end{bmatrix} \tag{10}$$

where ${}^A R_B \in \mathbb{R}^{3\times3}$ is the rotation matrix between frames A and B, and $S\left({}^A r_{AB}\right) \in \mathbb{R}^{3\times3}$ is a skew symmetric matrix built from the vector ${}^A r_{AB} \in \mathbb{R}^{3\times3}$ linking the origins of frames A and B, expressed in the coordinates of frame A.

The velocity vector is defined as follows:

$$V_B^r = \left[\dot{q}_1^r,...,\dot{q}_n^r, V_v, V_{B_1}^{rT},...,V_{B_n}^{rT}\right]^T$$

where $\dot{q}_j^r$ are the joint velocities, and the $V_{B_j}^r \in R^6$ vectors represent the velocity of each frame Bj.

The following relates the velocity propagation along the structure:

$$V_{B_{j+1}}^r = z\,\dot{q}_{j+1}^r + {}^{B_j}U_{B_{J+1}}^T V_{B_j}^r \quad (11)$$

In general, we can write the system in a matrix form by using the Jacobian matrix:

$$V_B^r = J_n \dot{q}^r \quad (12)$$

with $V_B^r = \left[\dot{q}_1, ..., \dot{q}_n, V_v^r, V_{B_1}^{rT}, ..., V_{B_n}^{rT}\right]^T$ and $J_n \in \mathbb{R}^{7n\times n}$ being the VDC Jacobian matrix of the system.

The dynamics of the j-th rigid body is given in the linear form by the following equation:

$$\begin{cases} F_{B_j}^* = M_{B_j}\dot{V}_{B_j} + C_{B_j}V_{B_j} + G_{Bj} \\ F_v^* = M_v\dot{V}_v + C_vV_v + G_v \end{cases} \quad (13)$$

with $M_{B_j}, M_v \in \mathbb{R}^{6\times 6}$ being the matrix of inertial term, $C_{B_j}, C_v \in \mathbb{R}^{6\times 6}$ the matrix of centrifugal/Coriolis term, $G_{B_j}, G_v \in \mathbb{R}^6$ the vector related to the gravity. The vector of resulting forces / moments acting on the rigid body is computed by an iterative process as follows:

$$\begin{aligned} &F_{B_n} = F_{B_n}^* \\ &F_{B_{n-1}} = F_{B_{n-1}}^* + {}^{B_{n-1}}U_{B_n}F_{B_n}^* \\ &\quad\vdots \\ &F_v = F_v^* = {}^vU_{T_1}F_{T_1} + {}^vU_{T_2}F_{T_2} - {}^vU_{B_3}F_{B_3} \\ &F_{B_2} = F_{B_2}^* + {}^{B_2}U_{T_2}F_{T_2} \\ &F_{B_1} = F_{B_1}^* + {}^{B_1}U_{T_1}F_{T_1} \end{aligned} \quad (14)$$

The dynamic model of the j-th rigid link (13) based on its required velocity is given by:

$$\begin{cases} F_{B_j}^{*r} = M_{B_j}\dot{V}_{B_j}^r + C_{B_j}V_{B_j}^r + G_{B_j} = Y_{B_j}\theta_{B_j} \\ F_v^{*r} = M_v\dot{V}_v^r + C_vV_v^r + G_v = Y_v\theta_v \end{cases} \quad (15)$$

where, $\theta_{B_j}, \theta_v \in \mathbb{R}^{13}$ is the parameters' vector of the j-th rigid link, and $Y_{B_j}, Y_v \in \mathbb{R}^{6\times 13}$ the dynamic regre s sor matrix.

Since the physical parameters of the j-th rigid body and the mobile platform are unknown and need to be estimated, then the estimated vectors $\hat{\theta}_{B_j}, \hat{\theta}_v$ are used and the required force/moment is obtained as follows:

$$\begin{cases} F_{B_j}^{*r} = Y_{B_j}\hat{\theta}_{B_j} + K_{B_j}\left(V_{B_j}^r - V_{B_j}\right) \\ F_v^{*r} = Y_v\hat{\theta}_v + K_v\left(V_v^r - V_v\right) \end{cases} \quad (16)$$

where, $\dot{\hat{\theta}}_{Bj} = \rho_{B_j}Y_{B_j}^T s_{B_j}$, $\dot{\hat{\theta}}_v = \rho_v Y_v^T s_v$ are the adaptation functions, and are chosen to ensure system stability, $s_{B_j} = \left(V_{B_j}^r - V_{B_j}\right), s_v = \left(V_v^r - V_v\right)$, and ρ_{B_j}, ρ_v, K_{Bj}, K_v are positive gains.

The vector of the required resulting forces/moments acting on the j-th rigid body is given by an iterative process (Zhu 2010, Brahmi et al. 2013) as in (14).

The dynamics of the j-th joint actuator is expressed by the following equation:

$$\tau_{aj}^* = J_{m_j}\ddot{q}_j + \xi\left(q_j, \dot{q}_j\right) \quad (17)$$

where, $\xi\left(q_j, \dot{q}_j\right)$ represents the friction and gravitation force / torque terms and J_{m_j} is the moment of inertia of the motor driving this joint. The dynamics (17) based on its required velocity is expressed in the linear form by the following:

$$\tau_{aj}^{*r} = J_{m_j}\ddot{q}_j^r + \xi\left(q_j^r, \dot{q}_j^r\right) = Y_{aj}\theta_{aj} \quad (18)$$

where, $\theta_{aj} \in \mathbb{R}^4$ is the parameters' vector of the j-th joint actuator, and $Y_{aj} \in \mathbb{R}^{1\times 4}$ is the dynamic regressor (row) vector, defined in (Zhu 2010, Brahmi et al. 2013). Since the physical parameters of the j-th actuator are unknown and need to be estimated, then the estimated vector $\hat{\theta}_{aj}$ is used and the dynamic (18) becomes:

$$\tau_{aj}^{*r} = Y_{aj}\hat{\theta}_{aj} + K_{aj}\left(\dot{q}_j^r - \dot{q}_j\right) \quad (19)$$

where, $\dot{\hat{\theta}}_{aj} = \rho_{a_j}Y_{a_j}^T s_{a_j}$ is the adaptation function, and is chosen to ensure system stability, $s_{a_j} = \left(\dot{q}_{rj} - \dot{q}_j\right)$, and ρ_{a_j}, K_{aj} are positive gains.

Finally, the input control torque at the j-th mobile manipulator's joint is computed from the desired torque obtained from (19) τ_{aj}^{*r} and the required force at cutting point B_j, identified $F_{B_j}^r$ as:

$$\tau = \tau_{aj}^{*r} + z^T F_{B_j}^r \quad (20)$$

Lemma 4.1: Consider the j-th rigid dynamics (13, 14) and the joint actuator dynamics (17), under the control design (16, 19 and 20) and the boundedness of the estimated parameters. The control objective is satisfied and the error tracking states are asymptotically stable.

Proof: Consider the Lyapunov function candidate:

$$V = \sum_{j=1}^{n} V_j + \sum_{j=1}^{n} V_{aj} + V_p \tag{21}$$

where V_j is a non-negative Lyapunov candidate function related to the j-th rigid link, V_{aj} is a non-negative Lyapunov candidate function of the j-th joint and V_p is a non-negative Lyapunov candidate function of the mobile platform. These three Lyapunov candidate functions are chosen as follow:

$$\begin{cases} V_j = \sum_{j=1}^{n}\left[\frac{1}{2}\left(V_{B_j}^r - V_{B_j}\right)^T M_{B_j}\left(V_{B_j}^r - V_{B_j}\right)\right] \\ \quad + \frac{1}{2}\sum_{i=1}^{13}\frac{\left(\theta_{B_{ji}} - \hat{\theta}_{B_{ji}}\right)^2}{\rho_{B_{ji}}} \\ V_{aj} = \sum_{j=1}^{n}\left[\frac{1}{2}J_{m_j}\left(\dot{q}_j^r - \dot{q}_j\right)^2 + \frac{1}{2}\sum_{i=1}^{4}\frac{\left(\theta_{aj_i} - \hat{\theta}_{aj_i}\right)^2}{\rho_{a_i}}\right] \\ V_p = \frac{1}{2}\left(V_v^r - V_v\right)^T M_v\left(V_v^r - V_v\right) + \frac{1}{2}\sum_{i=1}^{13}\frac{\left(\theta_{v_i} - \hat{\theta}_{v_i}\right)^2}{\rho_{v_i}} \end{cases} \tag{22}$$

where $\theta_{B_{ji}}, \hat{\theta}_{B_{ji}}, \theta_{v_i}, \hat{\theta}_{v_i}, \theta_{aj_i}$ and $\hat{\theta}_{aj_i}$ are the i-th elements of the corresponding vector parameters.

The first derivative of the Lyapunov candidate function (21) is given as follows:

$$\dot{V} = \sum_{j=1}^{n} \dot{V}_j + \sum_{j=1}^{n} \dot{V}_{aj} + \dot{V}_p \tag{23}$$

By using the definition of the virtual power and the choice of the parameter function adaptation as in (16) and (19); it is straightforward to prove that $\dot{V}$ is always decreasing and is given as follows:

$$\begin{aligned} \dot{V} = &-\sum_{j=1}^{n}\left(V_{B_j}^r - V_{B_j}\right)^T K_{B_j}\left(V_{B_j}^r - V_{B_j}\right) \\ &-\sum_{j=1}^{n} K_{a_j}\left(\dot{q}_j^r - \dot{q}_j\right)^2 - \left(V_v^r - V_v\right)^T K_v\left(V_v^r - V_v\right) \end{aligned} \tag{24}$$

The stability analysis shows that $\dot{V}$ is always decreasing and the system is asymptotically stable in the sense of Lyapunov. The reader can found the detailed proof stability in (Zhu 2010).

5 EXPERIMENTAL RESULTS

Experimental implementation is carried out on a 3-DOF MMR as illustrated in Figure 3. A Zigbee technology communication is used between the application program implemented in Simulink Matlab® and the mobile manipulator robot. The VDC approach is implemented in real time using Real-Time Workshop (RTW) of Mathworks®. Figure 3 shows the complete structure design of the control. This block diagram consists of Zigbee communication, low level (LL) controller (PI controller) and High level (HL) controller (virtual decomposition control) and measurement sensors (encoders).

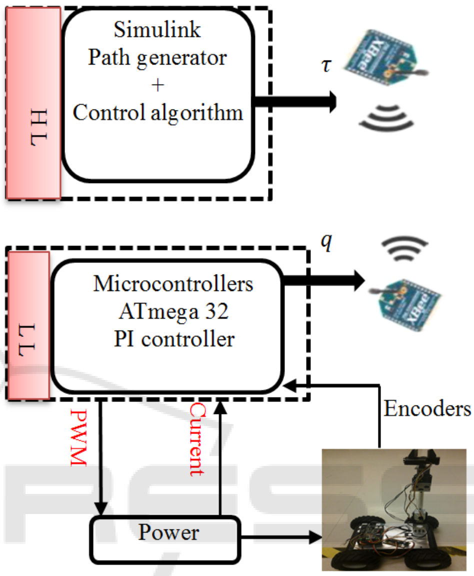

Figure 3: Real-time setup.

The control strategy was tested on 3-DOF mobile manipulator robot to track a desired trajectory in Cartesian space presented in Figure 4. The two wheels of the j-th mobile manipulator robot platform are actuated by two DC-motors HN-GH12-2217Y (DC-12V-200RPM 30:1) and its angular positions are given by using encoder sensors (E4P-100-079-D-H-T-B). All joints of the arm manipulator are actuated by Dynamixel motors (MX-64), this actuated gives the measurement of different parameter's as the angular position, the angular velocity, the torque and many others parameters used in the control and analysis. In this experimental test the Dynamixel motors are configured to be controlled on torque mode and are linked to ATmega 32 via TTL level multi drop bus.

The starting point is $P_{ei} = (0.14, -0.02, 0.4214)$, the final point is $P_{ef} = (7.8, -0.28, 0.4759)$, without end-effector orientation along X, Y or Z-axis and the actual end-effector mobile manipulator robot position is $P_{ef} = (0.18, -0.045, 0.3565)$. The inverse kinematics is used to transform the trajectory generated in the workspace to the joints space. The controller gains are chosen as follows:

$$K_p = (21.2, 8, 130, 3.7, 3.7), K_v = 0.8, K_{B_j} = 0.7, K_{aj} = 0.8.$$

The sampling time is set to 0.015 seconds.

The trajectory tracking in the Cartesian space is presented in Figure 4 and Figure 5 (a-b-c). It can be seen a good position tracking from Figure 5 (a-b-c). This good tracking is confirmed by the related errors between the desired values and the real ones shown in Figure 5 (d-e-f). All the input torques of the three joints of the arm manipulator and that of the right/left wheels are illustrated in Figure 6 (a-b-c-d-e).

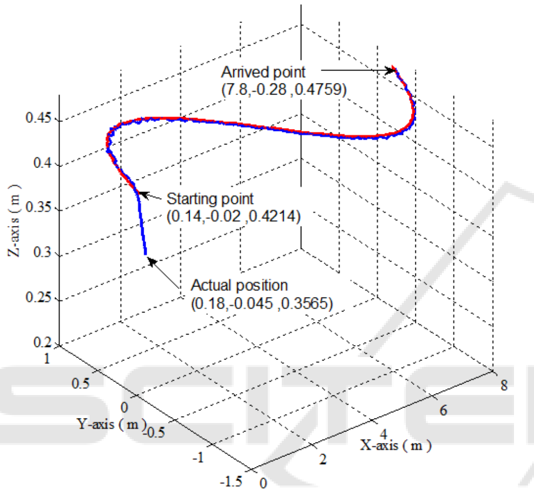

Figure 4: Desired trajectory of manipulator's end effector.

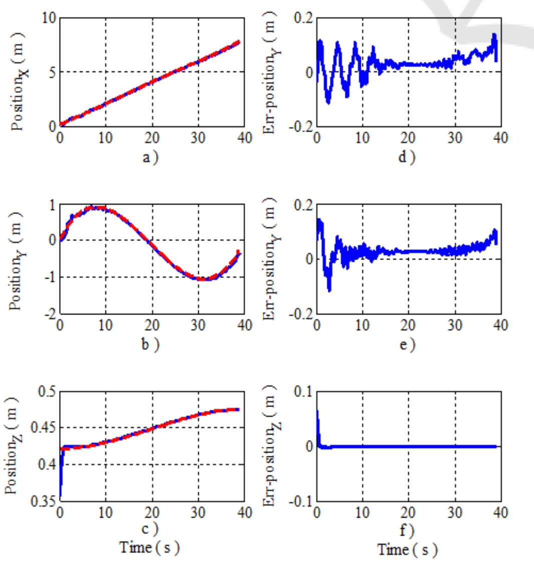

Figure 5: (a) Tracking trajectory of x-position, (b) Tracking trajectory of y-position (c) Tracking trajectory of z-position, (d) Tracking error of x-position, (e) Tracking error of y-position (f) Tracking error of z- position.

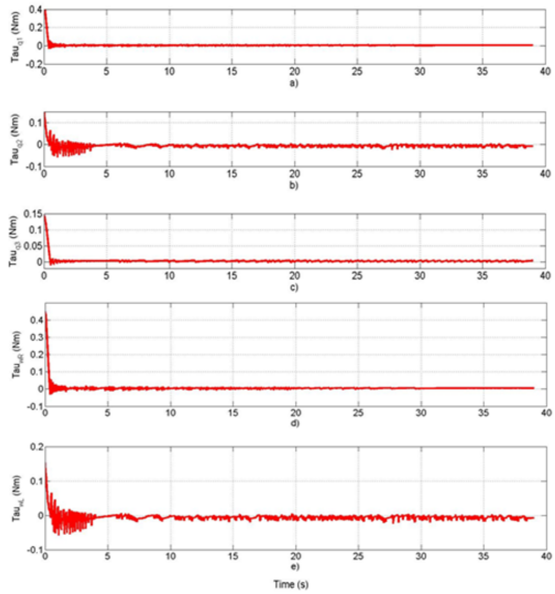

Figure 6: (a) The input torque of the joint 1, (b) The input torque of the joint 2 (c) The input torque of the joint 3, (d) The input torque of the right wheel 1, (e) The input torque of the left wheel.

6 CONCLUSIONS

In this paper, a decentralized control based on the virtual decomposition strategy was presented to control three degrees of freedom mobile manipulator robot to track desired trajectories generated in Cartesian space. The control law is designed based on the virtual decomposition approach, and the global stability of the systems is proven through the virtual stability of each subsystem. The proposed control design ensures that the workspace position error converges to zero asymptotically. The experimental results showed the effectiveness of this control approach where the tracking errors of the desired trajectory in workspace converge to zero.

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