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HTG-Based Kinematic Modeling for Positioning of a Multi-Articulated Wheeled Mobile Manipulator

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E. Gorrostieta-Hurtado · S. Tovar-Arriaga ·
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Abstract This paper presents a novel methodology for positioning an explosive ordnance device (EOD) which consists of a mobile manipulator with 12° of freedom. The approach uses an extension of a homogeneus transformation graph (HTG) which can be used in the kinematic modeling of mobile manipulators and unmanned aerial vehicles. In this approach the complete kinematics is modeled as one unit in contrast to previous approaches where the manipulator and mobile body are decoupled. The system is tested in several escenarios (simulated and real experimentation) like approaching to an explosive device location on the plane as well as in slope ways, climbing stairs, lifting itself and manipulating procedures. All the aforementioned scenarios were developed using the HTG which establishes the appropriate transformations and interaction parameters of the coupled system. Finally, the system is tested (simulated and real experimentation) for positioning its end device in a target with a RMS positioning average error ofr 7.91 mm which is acceptable for this kind of devices.

1 Introduction

A mobile manipulator is rigid robotic manipulator mounted atop of a wheeled mobile platform. In comparison to fixed-base manipulators, such a combined system is able to perform manipulation tasks in larger areas with high versatility. Therefore, mobile manipulators are useful in handling dangerous devices which are often called explosives ordnance devices (EOD). Those devices are used by many national forces around the world [1, 2]. The modular robot concept could be traced back to the 1970's [3]. Nevertheless, these kinds of robots are normally designed for tele-operated tasks [4–6].

When the base is a wheeled platform subject to nonholonomic constraints, the robot is referred to as a nonholonomic mobile manipulator. Several publications have been made about locomotion of mobile manipulators, being Yamamoto's work the most cited [7]. Mazur and Bayle et al. have written several papers in relation to control strategies and path following [8–10].

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It is only until 1988 where the dynamic behavior of mobile manipulators, was considered [11]. In 1989, Wiens [12] studied dynamic coupling between a planar vehicle and a one-link manipulator on the vehicle. Further works include dynamic model of some specific type [13–15]. Reactive motion has been studied for mobile manipulators in the case of omnidirectional wheeled platforms using a dynamical model [16]. In [17] Li et al. develop a reduced model for mobile manipulators such that Markovian theory can be used to model the fault tolerant considering a more realistic element-wise way to describe the transition-rate uncertainty.

Building up the dynamic model of a nonholonomic mobile modular manipulator is a challenging task due to the interactive motions between the modular manipulator and the mobile platform, as well as the nonholonomic constraints of the mobile platform [18]. Also a trajectory following becomes even more complex and difficult to achieve.

Published works, focused on control, kinematic redundancy, tracking trajectories and manipulability [8, 19–21], are mainly about mobile planar manipulator (not considering the load and operation cases) where the manipulator and the mobile dynamics are taken into account separately. Advanced studies have been carried out for controlling multiple robot manipulators grasping a common object which are robust to external disturbances [22, 23]. In [24] effective adaptive robust-control strategies were presented to address the force/motion control of holonomic-constrained noholonomic mobile manipulators in the presence of uncertainties and disturbances.

HTG is the abbreviation of Homogeneous Transformation Graph introduced by Paul R.P. [25] for fixed manipulators. The HTG, published in our previous works [26–29], contemplate systems about global coordinates, local coordinates and base coordinates of manipulators, which allows to use such a diagram in UAV's, mobile manipulators and other systems that consider complex manipulators, including objects that are attached to the end effector. In the present work, a kinematic interaction table was developed that allows to formulate a diagram that considers the base coordinates of the manipulators about the local coordinates of a mobile platform in relation to the global coordinates.

This paper shows the development of a modeling methodology for mobile manipulators applied in the mechatronic design of a multi-articulated wheeled mobile robot manipulator called MMR12-EOD. This robot will be used in tasks like positioning, handling and transporting of explosive devices. Due to its configuration, the robot is capable to do complex movements like climbing stairs of moving along terrains full of obstacles. One characteristics of our system is that the complete kinematic is modeled as one unit in contrast to previous works where the manipulator and mobile body are decoupled.

2 Methodology

In this section, a modeling methodology for wheeled mobile manipulators is presented. This methodology is organized in the following steps: preliminary analysis, master map, position and orientation diagram, homogenous transformation graph (HTG), kinematics schemes of operation scenarios, kinematics interactions, forward and inverse kinematic, constraints, dynamic parameters.

2.1 Preliminary Analysis

The MMR12-EOD robot is capable of doing locomotion on different types of surfaces by means of its action wheels. The wheels must be mounted on devices that allow relative motion between their guiding point and the surface (it has one rolling contact point) [30]. These characteristics allow modeling the system, but the slippage of the wheels makes it difficult due to the error presented in the robot autolocation. Figure 1 shows that the mobile platform has 4 dof, the manipulator has 4 dof and the added subsystem has 4.

The requirements of the MMR12-EOD robot are: average velocity of 0.5 m/s and requires supporting a load of 10 kg at its end effector.

The system contains different kinds of sensors which are: absolute encoder that measures the displacement angle of joint 1. Two inductive sensors used to measure the height of link 2 in its minimum and maximum extension. Proximity sensor that measures the operation range of prismatic joint 2. Two absolute encoders for joint 3 and 4, one each. Six absolute encoders sen-cos in each servomotor of the actuated wheels and four more in each lifting arm.

Fig. 1 MMR12-EOD robot. **a** Isometric view (*shows the rotation angle around the local coordinates*), **b** *top view showing the alternate actuated wheels*
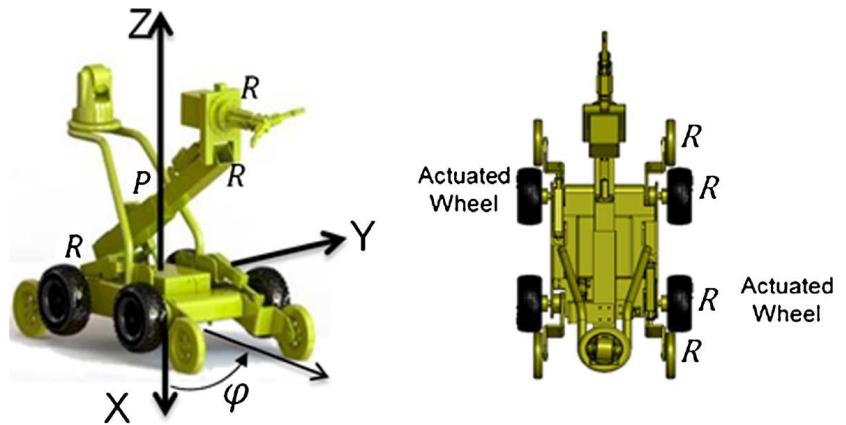
2.2 Master Map

The master map is a diagram that shows an overview of the model development, from which its subsystems and homogenous transformations are identified. First, the external and internal constraints are shown, being the first of them related to considered surface for the localization of the local coordinates in reference to the global coordinates. The internal restrictions are proposed according to the nonholonomic features of the mobile platform. Then, the scheme is classified with the nomenclature M-MMR-"add-subsystem", where M is the manipulator, MMR is the mobile body and any other add-subsystem, like a robotic arm. In case that another subsystem is added to the system, e.g. a second manipulator, the homogeneous transformation will be referenced to the local coordinates "C". The master map has stages regarding to subsystems for conventional mobile manipulators in relation to the orientation, approaching and manipulation tasks, in this case the mobile manipulator has an added subsystem formed by 2 coupled lifting arms, which will be considered for lifting and climbing tasks.

In order to model the MMR12-EOD robot, 7 stages are considered in 5 real operation scenarios, in which the assessment of behavior from the full system with load and without load are included. For this robot, the stages are as follows:

a) The added subsystem is considered in neutral position and in operation, related to the local coordinate "C". The added subsystem is called "A" in the master map. This stage is neglected if the manipulator does not have any added subsystem.

b) The manipulator uses just its degrees of freedom to do tracking trajectories tests, in relation to the "0" coordinate (origin), which is located on the manipulator's base.

c) The mobile platform is moved forward with the mounted manipulator and does a tracking trajectory test, from coordinate "C" to global coordinate "G⁴".

d) Considering the coupled system without advance of the mobile platform, the manipulator do the tracking trajectories test, assuming that the mobile platform rotates about its axis, in relation to the local coordinate "C".

e) The mobile platform is moved forward coupled with the manipulator and does a tracking trajectory test, from "C" coordinate to the "G4" global coordinate.

f) The coupled system is moved following a straight line and its manipulator is moved in relation to "G⁴".

g) The coupled system does tracking trajectories tests, in relation to the end effector regarding the "G4" coordinate.

The mentioned stages related to the subsystems and the homogenous transformations are shown in Fig. 2.

2.3 Position and Orientation Diagram

Figure 3 presents a general description of the position and orientation of the system, depicted by the relation of 4th transformation of global coordinates regarding to $GA_{(4)} = \text{Trans}\left(x_G^{(4)} y_G^{(4)} z_G^{(4)} \right) GA_{(3)}$.

2.4 Homogeneous Transformations Graph (HTG)

The third step of the methodology is the homogenous transformation graph that in modular way allows
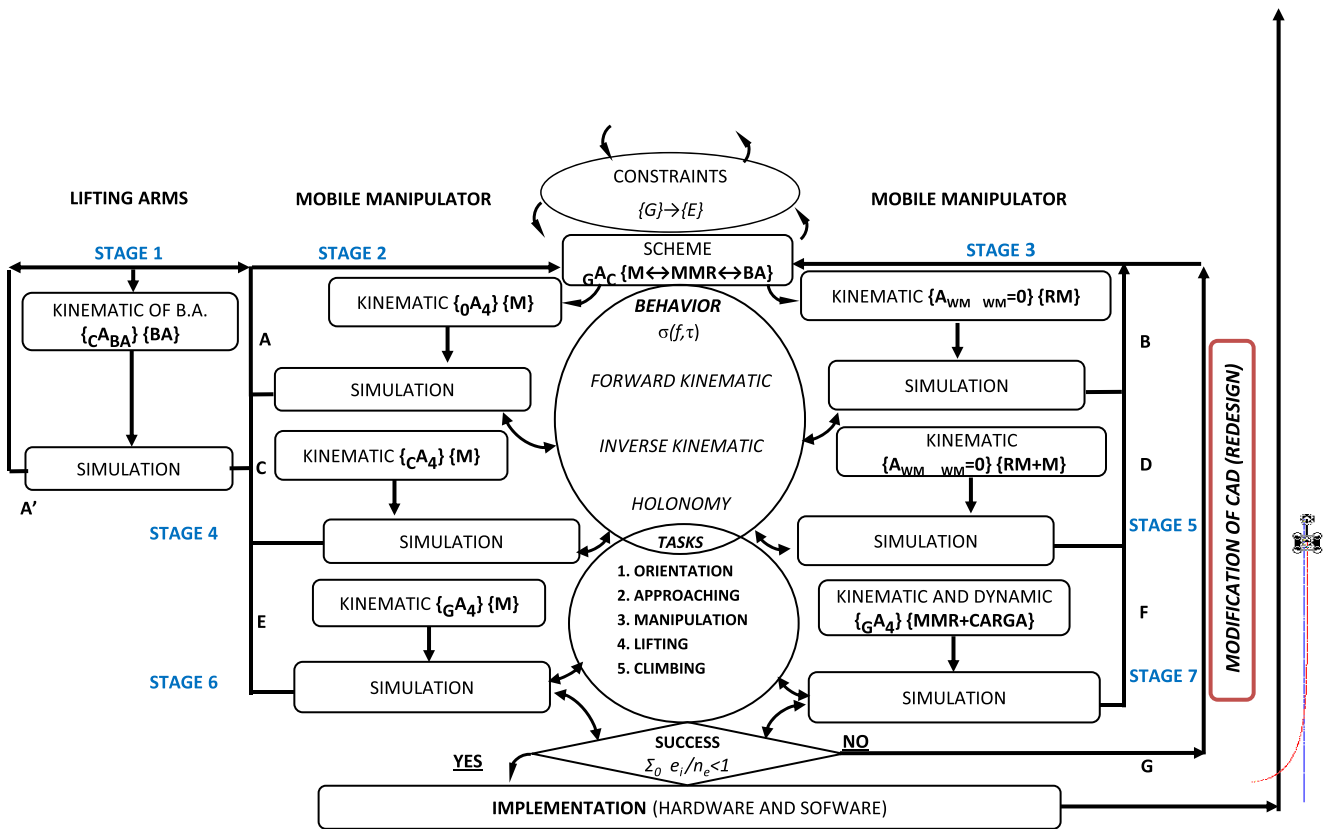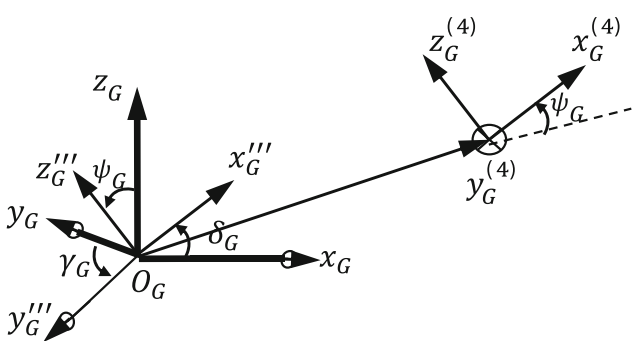
Fig. 2 Master map of the MMR12-EOD robot. It is a diagram that shows the development of the mobile manipulator modeling and every subsystem is identified together with the homogeneous transformation graph (HTG). Each stage is validated through simulation

to structure the subsystems that formed the mobile manipulator plus the added subsystem. This graph is an extension of transformation graph proposed to the manipulators kinematic by Robert Paul, in 1983 [25] and used in several works by Tadeusz Skodny [31]. The extension of Pauli's graph allows getting the homogenous transformation graph for the kinematic modeling of wheeled mobile manipulators with any added subsystem. These transformations are

the central part of the methodology, because they give the relations with the "0" manipulator coordinates, "C" of mobile platform, the transformations of wheels and of lifting arms regarding to "C" and "C" regarding to "G^4" as shown in Fig. 4. Afterwards are assignment coordinates systems to determine points that allow by mean of the suitable relations, obtain the coupled kinematic modeling of full system.

2.5 Kinematics Schemes of Operation Scenarios

In order to do the kinematic schemes of 5 real operation scenarios of the MMR12-EOD robot, it is necessary to consider its design parameters, shown in Table 1.

2.6 Kinematic Interactions

Table 2 shows the kinematic interaction parameters that are obtained by analyzing the subsystems coupling of the MMR12-EOD robot.

Fig. 3 Description of the manipulator position movement in relation to global coordinates

Fig. 4 HTG for mobile manipulators. It allows structuring the subsystems that formed the mobile manipulator (*wheels and manipulator*) plus the added subsystem (*lifting arms*)
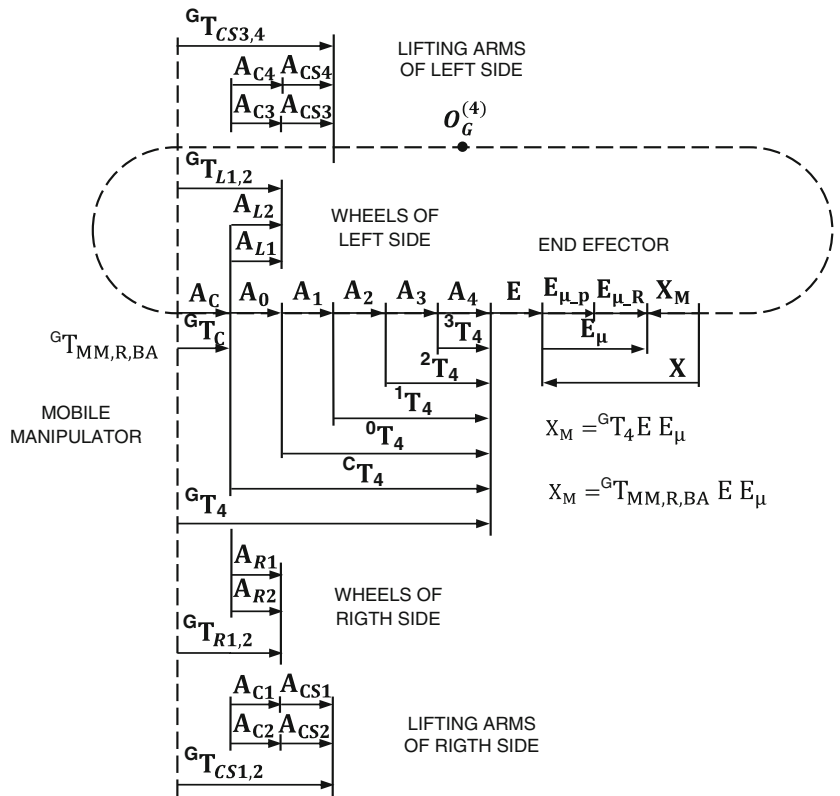
2.7 Forward and Inverse Kinematics

2.7.1 Forward Kinematics

Based on the homogenous transformation graph and the kinematic interactions table is the forward kinematic developed, being with the transformation A_C, which is the coordinate "C" and from these are depicted the transformations of the wheels, the lift arms and the manipulator, considering the end effector "E" with the load "Eμ", as it is shown in Figs. 5 and 6.

a) *Mobile platform*

The homogenous transformation of the mobile platform is $A_C = \left(x_G^{(4)} y_G^{(4)} z_G^{(4)} \rightarrow x_C y_C z_C \right)$, where $A_C =$

Table 1 Design parameters of mobile manipulator MMR12-EOD

Configuration	Type	Degrees of freedom
Mobile platform not articulated	Diferential locomotion	4 (X, Y, Z, φ)
Manipulator	Articulated	4 (RPRR)
Lifting arms	Articulated	4 (RR)
Total		12

$\text{Trans}(x_{C0}, y_{C0}, z_{C0})\text{Rot}(z, \varphi)\text{Trans}(0, 0, \Delta\lambda_C)$ and its parameters are: x_{C0}(variable), y_{C0}(variable), $z_C = \lambda_{C0} + \Delta\lambda_C$, $z_{C0} = \lambda_{C0}$(const > 0), θ_{C1}(variable), 1_{CS1}(const. > 0), φ(variable). The increment of λ_C depends on the following relation:

$$\Delta\lambda_C = \begin{cases} l_{CS1}S_{C1} - \lambda_{C0} + r \\ \text{for } l_{CS1}S_{C1} - \lambda_{C0} + r \geq 0, \ r_1 = r_2 = r_3 = r_4 = r = \text{constant} > 0 \\ 0 \text{ for other case} \end{cases}$$

(1)

Then, the transformation of the local coordinate is obtained, $GT_C = A_C$ and so the transformations of the right and left wheels, $GT_R = A_C A_R$ y $GT_L = A_C A_L$.

b) *Lifting arm in slopping surfaces*

The homogeneous transformation for lifting the arm is developed in relation to the local coordinate "C". In Fig. 7, it is shown the lateral view of the mobile manipulator in the elevation position, were increment of λ_C is presented.

The parameters for the lifting arm of the right front side are as follows: A_{CS1} : θ_{CS1}(variable), l_{CS1}(const > 0), therefore the transformation of arm

Table 2 Kinematics interactions of the MMR12-EOD robot. The parameters and their interaction as coupled system are used as basis of the forward and inverse kinematics

| Manipulator				Interaction	Mobile platform and lifting arms						
Link	α_i [rad]	l_i [m]	λ_i [m]	θ_i [rad]	φ_i [rad]	ψ_i [rad]	x_i [m]	y_i [m]	z_i [m]	b_i [m]	d_i [m]
C	–	–	–	–	$\varphi_c(\theta_R, \theta_L)$	$\psi = $-var	x_c	y_c	$\lambda_c = 0.15$, $\lambda_c(\theta_{cs})$	–	–
W_R	–	–	–	$\theta_{R1,2}$	–	–	–	–	–	-$b_{R1,2}$	
W_L	–	–	–	$\theta_{L1,2}$	–	–	–	–	–	$b_{L1,2}$	
C_1	-$\pi/2$	$l_{cs} = 0.33$	0	$\theta_{C1,2,3,4}$	–	–	–	–	–	–	–
CS_1	0	$l_{csi} = 0.44$	0	$\theta_{Cs1,2,3,4}$	–	–	–	–	–	–	$d_{R1,2}$ $d_{L1,2}$
0	$\pi/2$	-$l_0 = -0.33$	$\lambda_0 = 0.16$	0	–	–	–	–	–	–	–
1	$\pi/2$	0	0	$\theta_1 = \theta_1' + 90°$	–	–	–	–	–	–	–
2	-$\pi/2$	0	$\lambda_2 = 0.4$	0	–	–	–	–	–	–	–
3	$\pi/2$	$l_3 = 0.15$	0	$\theta_3 = $-var	–	–	–	–	–	–	–
4	0	0	0	θ_4	–	–	–	–	–	–	–
E	0	0	$\lambda_5 = 0.38$	0	–	–	–	–	–	–	–
$E_{\mu P}$	0	0	$\lambda_6 = 0.05$	0	–	–	–	–	–	–	–
$E_{\mu R}$	$\pi/2$	0	0	θ_μ	–	–	–	–	–	–	–

1 in relation to the global coordinate is $GT_{CS1} = A_C A_{C1} A_{CS1}$. Similarly are the relations for the second, third and fourth lifting arm carried out.

c) *Manipulator*

It is presented the respective transformations of the 4 degree of freedom regarding to coordinate "0",

in relation to the "C" coordinate. The homogenous transformation from "C" to "0", $A_0 = (x_C y_C z_C \rightarrow x_0 y_0 z_0)$, depends on the following parameters: $\theta_0 = 0°$, $\lambda_0 = $ const > 0, $l_0 = $ const $< 0 \alpha_0 = 90°$, $_1 = (x_0 y_0 z_0 \rightarrow x_1 y_1 z_1)$, depends on the following parameters: θ_1(variable), $\lambda_1 = 0$, $l_1 = 0 \alpha_1 = 90°$, the transformation $A_2 = (x_1 y_1 z_1 \rightarrow x_2 y_2 z_2)$, depends on

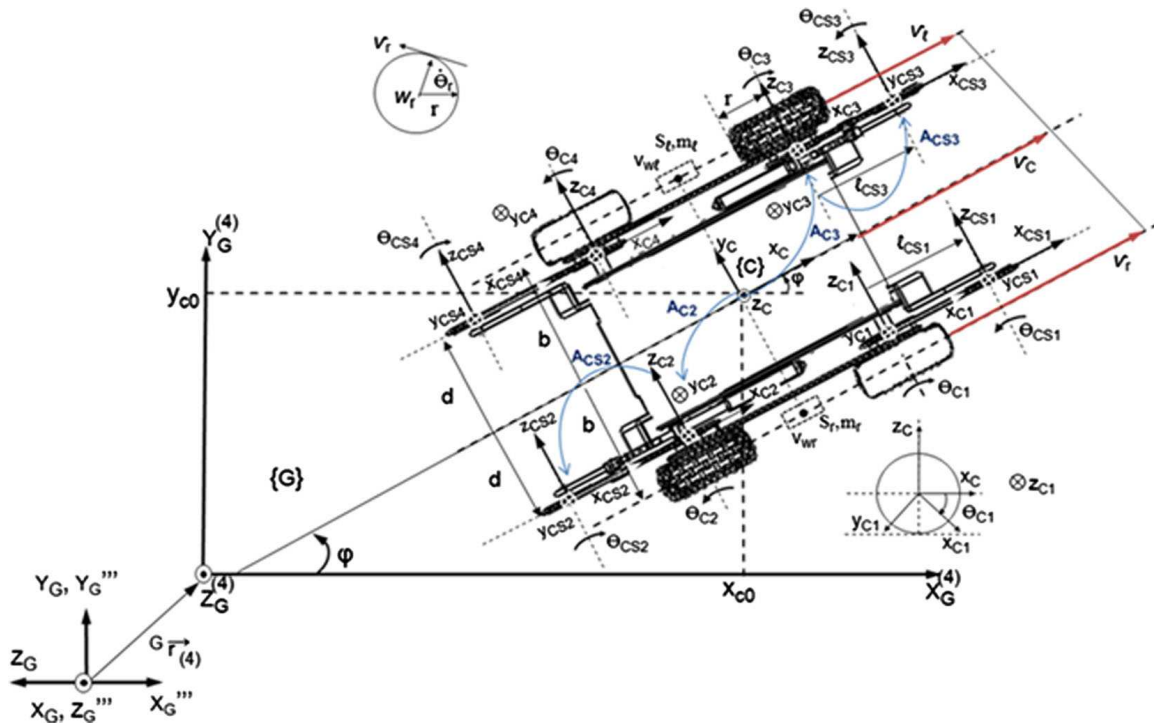**Fig. 5** Lateral view of the MMR12-EOD robot in lifting position
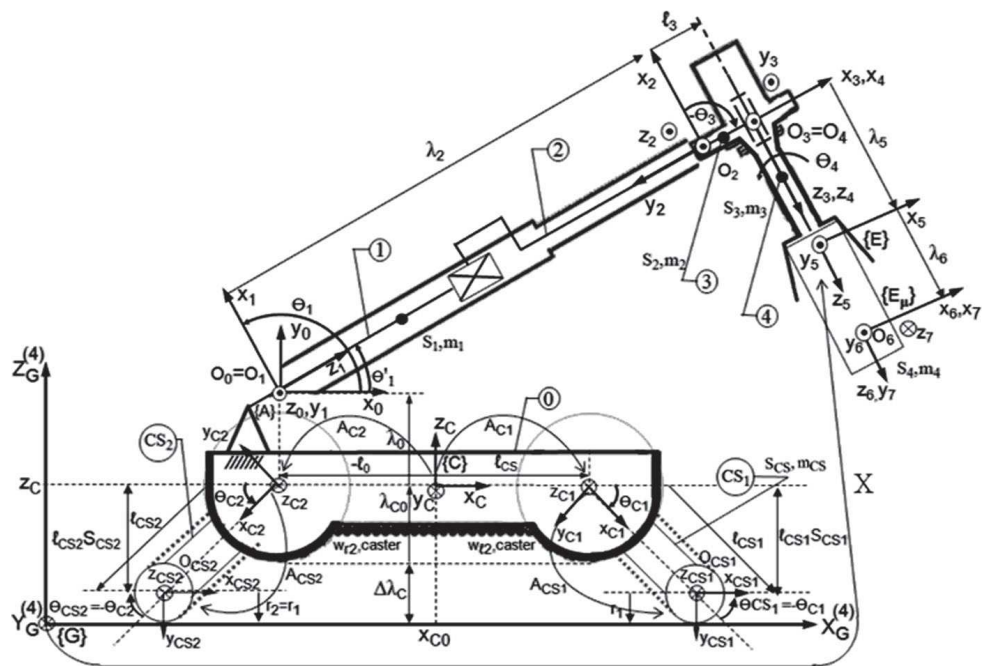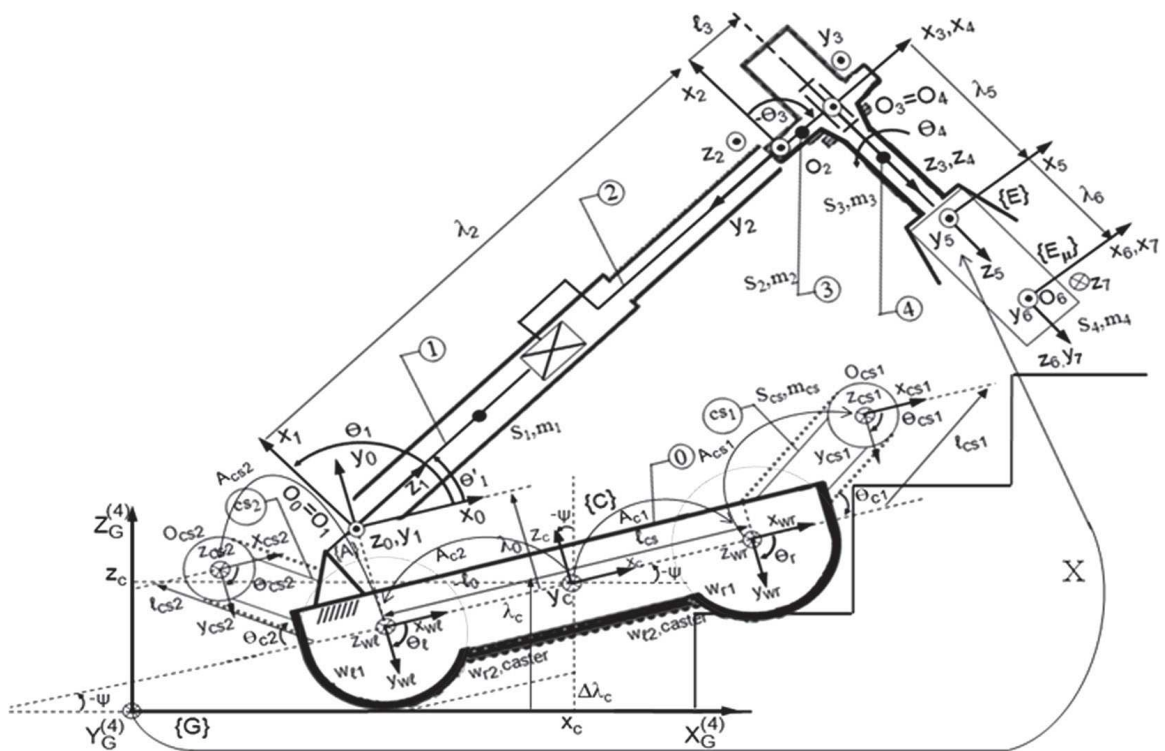
Fig. 6 MMR12-EOD robot in top view

Fig. 7 Lateral view, driving the MMR12-EOD robot in climbing operation

the following parameters: $\theta_2 = 0°$, λ_2(variable), $1_2 = 0\alpha_2 = -90°$, the $A_3 = (x_2y_2z_2 \rightarrow x_3y_3z_3)$ transformation depends on the following parameters: θ_3(variable), $\lambda_3 = 0, 1_3$(const > 0), $\alpha_3 = 90°$ and the transformation $A_4 = (x_3y_3z_3 \rightarrow x_4y_4z_4)$ depends on the following parameters:: θ_4(variable), $\lambda_4 = 0, 1_4 = 0\alpha_4 = 0°$.

The transformations of end effector in relation to the 4 degree of freedom of manipulator are given by: $E = (x_4y_4z_4 \rightarrow x_5y_5z_5)$, where, $E = Trans(0,0,\lambda_5)$ and its parameters: $E : \theta_5 = 0°, \lambda_5 = const > 0, 1_5 = 0\alpha_5 = 0°$. In order to obtain the homogeneous transformation that relates the load to the end effector the next equation is used: $E_\mu = E_{\mu P}E_{\mu R}$, where E_μ is the total load, constituted by $E_{\mu P}$ y $E_{\mu R}$, which are

the load deployed as prismatic joint and rotational, respectively. The parameters of prismatic joint are the following: $E_{\mu P}$: $\theta_6 = 0°, \lambda_6 = const > 0, 1_6 = 0\alpha_6 = 0°$, and the parameter of rotational joint is: $E_{\mu R}$: $\theta_7 = 0°, \lambda_7 = 0, 1_7 = 0\alpha_7 = 90°$.

The transformation of the manipulator is T_4, using the trigonometric simplification $Cos(A + B) = C_A C_B - S_A S_B = C_{AB}$, $Sin(A + B) = C_A S_B + S_A C_B = S_{AB}$ is the transformation obtained from manipulator to global coordinates given by $GT_4 = A_C CT_4$. The transformation of the end effector with the load is determined by $E_\mu = E_{\mu P}E_{\mu R}$. Finally, the homogenous transformation from load "X" in the end effector regarding to global coordinates is obtained and presented in Eq. 2.

$$X_M = GT_4 E\ E_\mu$$

$$= \begin{bmatrix} S_4S_C + C_CC_{13}C_4 & C_CS_{13} & C_CC_{13}S_4 - C_4S_C & x_C + C_C(S_1\lambda_2 + 1_3C_{13} - 1_0) + C_C\lambda_5S_{13} + C_C\lambda_6S_{13} \\ S_CC_{13}C_4 - C_CS_4 & S_CC_{13} & S_CC_{13}S_4 + C_4C_C & y_C + S_C(S_1\lambda_2 + 1_3C_{13} - 1_0) + S_C\lambda_5S_{13} + S_C\lambda_6S_{13} \\ S_{13}C_4 & -C_{13} & S_{13}S_4 & z_{C0} + \Delta\lambda_C + \lambda_0 - \lambda_5C_{13} - C_1\lambda_2 + 1_3S_{13} - \lambda_6C_{13} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$(2)$$

2.7.2 Inverse Kinematics

The inverse kinematics scheme is shown in Fig. 8. From this scheme, the equations that relate the Cartesian coordinates form task space regarding to joint parameters are obtained and listed from Eqs. 3–11. The equations show how the mobile manipulator estimates the coordinates of end effector to the Cartesian coordinates. The inverse kinematic was developed using the homogenous transformations.

$$\varphi = \tan^{-1}\left(\frac{dy}{dx}\right) \tag{3}$$

$$\theta_3 = \cos^{-1}\left[\frac{dx^2 + dy^2 + dz^2 - \lambda_2^2 - \lambda_5^2}{-2\lambda_2\lambda_5}\right] \tag{4}$$

$$\lambda_2 = \frac{d_Z + \lambda_0 - \lambda_5C_3 + 1_3S_3}{C_3} \tag{5}$$

$$E = \tan^{-1}\left(\frac{1_3}{\lambda_5}\right); \ K = 180 - 90 - E1; \ h = \left(\frac{1_3}{S_E}\right); \tag{6}$$

$$P = 180 - K - q_3; \ r = \sqrt{h^2 + d_2^2 - [2hd_2C_{P1}]}; \tag{7}$$

$$d = \cos^{-1}\left(\frac{h^2 + r^2 - d_2^2}{2hr}\right); \ q_1' = 180 - P - d_1; \tag{8}$$

$$q_1'' = \sin^{-1}\left(\frac{d_z + d_o - d_c}{r}\right); \ q_1 = q_1' + q_1'' \tag{9}$$

$$x_C = d_X - C_C(\lambda_2S_1 - 1_0 + 1_3C_{13} + \lambda_5S_{13}) \tag{10}$$

$$y_c = d_y - S_c(\lambda_2S_1 - 1_0 + 1_3C_{13} + \lambda_5S_{13}) \tag{11}$$

Last equations where obtained by means of the graphical scheme presented in Fig. 8, where Eq. 7 represents the variables P and r in degrees that were assigned to help to obtain the angles to the deduction of the inverse kinematics.

2.8 Constraints

The differential kinematics in relation to $Z_G^{(4)}$ can be calculated based on nonholonomic constraints. Those
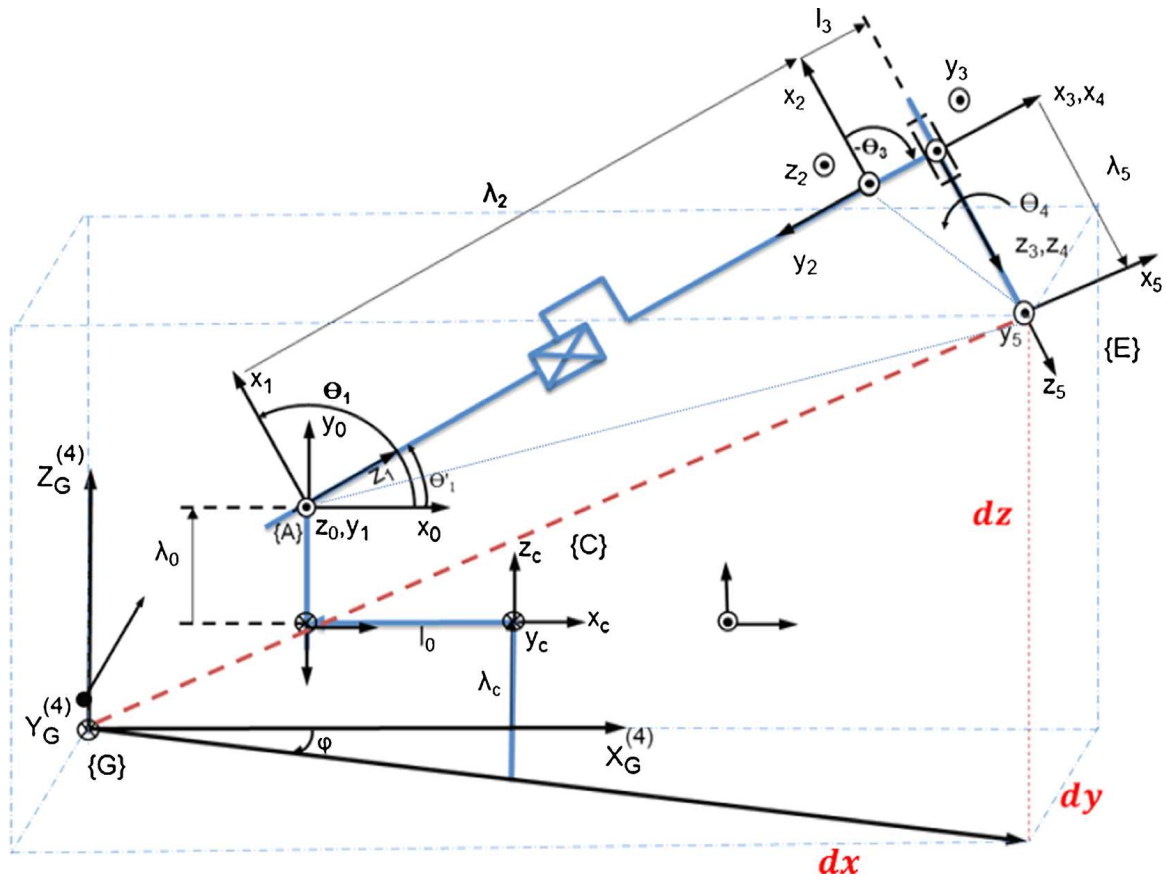
Fig. 8 The inverse kinematic scheme was developed using homogeneous transformations and the derived equations of the forward kinematics

do not have integral solution and represent more degrees than the controllable degrees of freedom [7, 25]. In order to relate the velocities from the system,

it is considered that the orientation angles regarding to global coordinates are; (x_G, δ_G) (y_G, φ_G) (z_G, γ_G), assuming that the position and orientation or local

Table 3 Constraints equations of the MMR12-EOD robot		
One constraint is that the mobile platform must move in the direction of the axis of symmetry of itself without sliding of any the wheels in relation to ground, where (x_{C0}, y_{C0}, z_{C0}) are the coordinates of the center of mass of mobile platform, φ is the heading angle of the platform measured from the $X_G^{(4)}$ axis of the local coordinates.	$\dot{y}_{C0} \cos \varphi - \dot{x}_{C0} \sin \varphi = 0$	(12)
The other two are the rolling constraints, i.e., the driving wheels do not slip, where θ_r, θ_1 are the angular displacement of the right and left wheels, respectively.	$\dot{x}_{C0} \cos \varphi + \dot{y}_{C0} \sin \varphi + \dot{\varphi} b = \dot{\theta}_r r$ $\dot{\varphi} = \frac{r}{2b}(\dot{\theta}_r - \dot{\theta}_1)$	(13) (14)

reference in relation to the global reference are constant in the robot movement, and $\dot{\theta}_{C1} = 0$, $\dot{\theta}_{CS1} = 0$. Table 3 shows the constraints equations [25]:

Next, the Eq. 15 shows the twelve variables for the Jacobian (16).

$$q = \begin{bmatrix} x_{C0} & y_{C0} & \varphi_C & \theta_r & \theta_1 & z_{C0} & \theta_{C1} & \theta_{CS1} & \theta_1 & d_2 & \theta_3 & \theta_4 \end{bmatrix}^T, \tag{15}$$
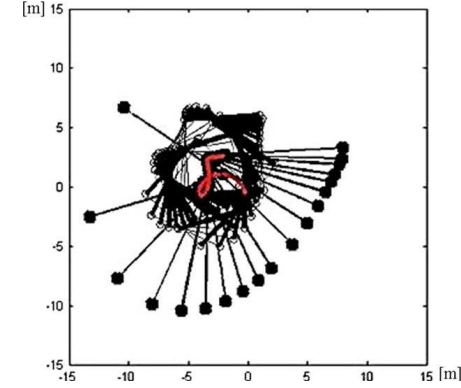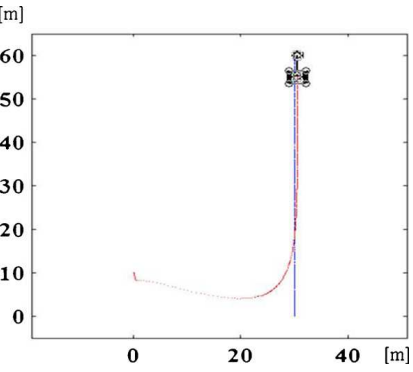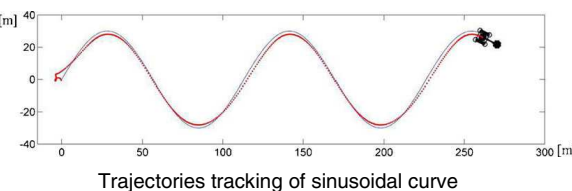
$$J = \begin{bmatrix} -\sin\varphi & \cos\varphi & 0 & 0 & 0 & 0\,0\,0\,0\,0\,0\,0 \\ -\cos\varphi & -\sin\varphi & -b & r & 0 & 0\,0\,0\,0\,0\,0\,0 \\ 0 & 0 & -1 & \frac{r}{2b} & -\frac{r}{2b} & 0\,0\,0\,0\,0\,0\,0 \end{bmatrix} \tag{16}$$

It is known that $J(q)\dot{q} = 0$ and as $J(q)$ is a square matrix, then: $J_1^{-1} = \frac{1}{|J_1|}[adj(J_1)]^T$, $[adj(J_1)]^T$, because of the determinant of J_1 results $|J_1| = -1$, then the mobile manipulator has good manipulability according to the mobile platform [13]. $J(q) = [J_1(q), J_2(q)]$. Finally we have $J_{12}(q) = -J_1^{-1}(q)J_2(q)$.

2.9 Dynamic Parameters

The dynamic model was done using Lagrange's computational algorithm, based on the homogenous transformations and the interactions table, which is presented in this work in 10 steps. We will use the letter

Table 4 Tasks of orientation and tracking trajectories

Trajectories tracking about its center

Sample time of: $t_m = 200\ s$. The reference C, is located in:
$y_{desired} = 0$
$x_{desired} = 0$
Mean error of 40 mm.

Following a straight trajectory

$t_m = 200\ s$. The reference, is located in:
$y_{desired} = t$
$x_{desired} = 30$
Mean error of 2.0 mm.

Trajectories tracking of sinusoidal curve

$t_m = 200\ s$. The reference, is located in:
$y_{desired} = 30\sin(0.25\ t)$
$x_{desired} = 40\cos(0.25\ t) + 2.5\ t$
Mean error of 2.37 mm.

L to describe each step. L1 is the description of each link of the interaction table HTG. L2 is the classification of the homogeneous transformation. L3 is the determination of the primary matrices of U_{ij}. L4 is the determination of the secondary matrices U_{ijk}. L5 describes the pseudo inertial matrices of each link. L6 is the inertia matrix $M(q) = [d_{ij}]$. L7 is the determination of the Coriollis and centrifuge forces parameters h_{ikm}. L8, is the determination the Coriollis and centrifuge forces. L9 is the determination of the gravity matrix $G(q) = [c_i]^T$ and L10 is the dynamic equation $V(q, \dot{q}) = [h_i]^T$.

$$M(q)\ddot{q} + V(q, \dot{q})\dot{q} + G(q) = E(q)\tau - A^T(q)\lambda \quad (17)$$

$$\begin{bmatrix} d11 & \dots & d112 \\ \vdots & \dots & \vdots \\ d121 & \dots & d1212 \end{bmatrix} \ddot{q} + \begin{bmatrix} h1 \\ \vdots \\ h12 \end{bmatrix} \dot{q} + \begin{bmatrix} c1 \\ \vdots \\ c12 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ \vdots & \vdots \\ 1 & 0 \\ 0 & 1 \\ \vdots & \vdots \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \tau_x \\ \vdots \\ \tau_4 \end{bmatrix} - \begin{bmatrix} -S_C & C_C & 0 & 0 & 0 & \dots & 0 \\ -C_C & -S_C & -b & r & 0 & \dots & 0 \\ 0 & 0 & b & 0 & r & \dots & 0 \end{bmatrix} \quad (18)$$

The dynamic equation is described in Eq. 17. Equation 18 shows a more detailed form of the corresponding matrices.

$$\ddot{q} = M(q)^{-1}[E(q)\tau - A^T(q)\lambda - V(q, \dot{q})\dot{q} - G(q)] \quad (19)$$

$$S(q) = \begin{bmatrix} -S_C & C_C & 0 & 0 & 0 & \dots & 0 \\ -C_C & -S_C & -b & r & 0 & \dots & 0 \\ 0 & 0 & b & 0 & r & \dots & 0 \end{bmatrix}. \quad (20)$$

2.10 Consolidation of Dynamic Equation

The two columns $S(q)$ are the null space of $A(q)$ and are linear independent. q could be expressed as a lineal combination of two columns of $S(q)$.

$$\dot{q} = S(q)\nu$$

After derivation, it turns out in:

$$\ddot{q} = S(q)\dot{\nu}(t) + \dot{S}(q)\nu(t)$$

Substituting it in Eq. 14 gives way to Eqs. 18 and 19:

$$S^T(q)$$
$$(M(q)S(q)\dot{\nu}(t) + M(q)\dot{S}(q)\nu(t) + V(q, \dot{q})\dot{q} + G(q))$$
$$= (E(q)\tau - A^T(q)\lambda)S^T(q) \quad (21)$$

$$S^T(q)\ (M(q)S(q)\dot{\nu}(t) + M(q)\dot{S}(q)\nu(t) + V(q, \dot{q})\dot{q}$$
$$+ G(q)) = \tau \quad (22)$$

In order to validate (22), it was verified that the corresponding inertia matrix M(q) satisfy the next properties: 1) it is square, 2) it symmetrical $M^T(q) = M(q)$, 3) it is not singular due to the fact that the determinant of the inertia matrix is positive and equal to the determinant of its transpose matrix $det(M(q)) = 8.0644e + 021 > 0 = det(M(q)^T) = 8.0644e + 021 > 0$, 4) it is positive defined $d_{11}(q) > 0$.

2.11 Real Experimentation and Positioning Simulation

The real experimentation and simulation of the mobile manipulator positioning is done according to five real operation tasks. In order to do these activities the control strategy published by Yamamoto was used [7], where the control and coordination of movement from mobile manipulators was presented in 2004. Using the vector in the state space $x = \begin{bmatrix} q^T & \upsilon^T \end{bmatrix}^T$, we can represent the constraints and movement equations from mobile manipulator in the state space:

$$\dot{x} = \begin{bmatrix} S\upsilon \\ f_2 \end{bmatrix} + \begin{bmatrix} 0 \\ (S^T M S)^{-1} \end{bmatrix} \tau \quad (23)$$

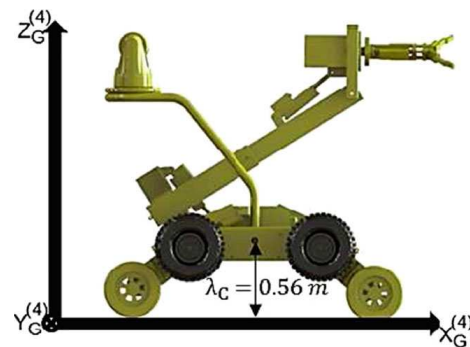where $f_2 = (S^T M S)^{-1}(-S^T M S\upsilon - S^T V)$. This equation is then simplified as:

$$\dot{x} = \begin{bmatrix} S\upsilon \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ I \end{bmatrix} u \quad (24)$$

Last equation is used to apply the feedback $\tau = S^T M S(u - f_2)$. According to Eq. 24 a new input u is
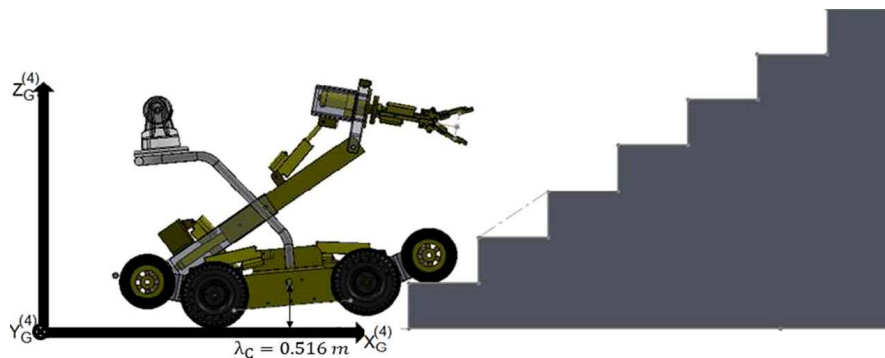
Table 5 Manipulation, lifting and climbing
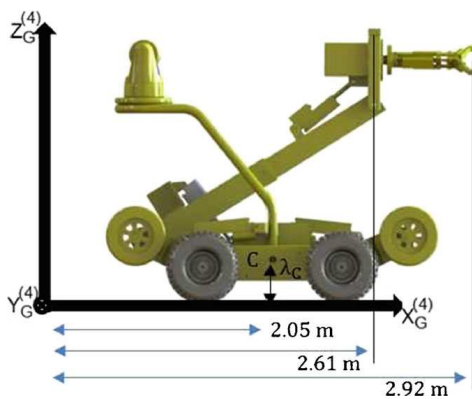
Mean error of 0.050 mm in thea manipulation task.

Mean error of 0.020 mm in the lifting task.

Mean error of 40 mm in the climbing task.

assumed, which linearizes (23). In this way we can use the desired trajectory y^d in order to feedback the error $e = y^d - y$.

$$\ddot{y} = v = \ddot{y}^d + K_d(\dot{y}^d - \dot{y}) + K_p(y^d - y) \qquad (25)$$

From Eq. 21, v, u and then $\dot{x}$ can be calculated. By integrating $\dot{x}$ then x is obtained.

a) Orientation (stage 2, task 1). The actuated wheels have differential steering, so that $v_r = -v_l$. It allows that the mobile platform rotates around its z coordinate, in an ideal diameter of $\phi = 1{,}130$ mm. It is assumed that the mobile manipulator movement is carried out horizontally and the wheel is in contact with the floor in only one point. Wheels deformation is not considered, meaning that the contact point with the floor is $v = 0$, there is no slippage, and the direction axis is orthogonal the surface. The wheels are connected by a rigid body (chassis).

b) Approaching / Trajectory tracking (stage 4, task 2). The system executes the tracking the desired trajectory, based on the transformation $GT_C =$

Table 6 Real experimentation of manipulation, lifting and climbing tasks

30 samples	Deviations	
1. In the test of orientation were measures errors of:	Error min. 40 mm	Error max. 80 mm.
2. Approaching (trajectories tracking).	Error min. 0.5 mm	Error max. 8 mm.
3. Manipulation (positioning).	Error min. 0.5 mm	Error max. 8 mm.
4. Lifting.	Error min. 4 mm	Error max. 6 mm.
5. Climbing.	Error min. 4.6 mm	Error max. 8 mm.

A_C, the mobile platform is moved according this equation: $q_{MR} = [xyz\varphi_C\theta_r\theta_1]^T$.

c) Manipulation (stage 4, task 3). In the rank: $x = 2.5$, $y = 2.5$, $z = 1.5$ m, the kinematic is given by: $X_M = GT_4E\ E_\mu$ by main the equation: $q_M = [\varphi_C\theta_1 d_2\theta_3\theta_4]^T$.

d) Lifting the mobile manipulator in the Rank from 0.15 up to 0.52 m. based in the transformation $GT_C = A_C$, z is given by $z_C = \lambda_{C0} + \Delta\lambda_C$ (which is variable), $z_{C0} = \lambda_{C0} = \text{const} > 0$, θ_{C1}(variable), $1_{CS1} = \text{const} > 0$, φ(variable), where the increment $\Delta\lambda_C$ of z, depends of lifting arms.

e) In the lifting test, the frontal arms raise the mobile manipulator from $\lambda_C = 0.15$ m to $\lambda_C = 0.47$ m. The mobile manipulator with mass m is moved on the slope with an angle ψ (to the horizontal) given by the transformation CT_{CS1}, and the equation $F_{\text{climb}} = mg(\sin\psi + \mu\cos\psi)$, where g is the gravity, when $\theta_{CS} > 60°$, $\lambda_C + (\Delta_C = 1_{CS1} + \sin\theta_{CS})$

3 Results

The reference values for every task were taken from the forward kinematics. The parameters for the local "C" coordinate, which is the base to obtain the reference values are the following: $A_C : x_{C0} = 2$, $y_{C0} = 2$, $z_C = \lambda_{C0} + \Delta\lambda_C$, $z_{CO} = \lambda_{C0} = 0.15$, $\theta_{C1} = \frac{\pi}{2}$, $1_{CS1} = 0.44$, $\varphi = \frac{\pi}{4}$, $\varphi = 20\pi$.

$$\Delta\lambda_C = \begin{cases} 1_{CS1}S_{C1} - \lambda_{C0} + r \\ \text{for } 1_{CS1}S_{C1} - \lambda_{C0} + r \geq 0, r_1 = r_2 = r_3 = r_4 = r = 0.08 \\ 0 \text{ other case} \end{cases}$$

(26)

a) Equation 27 shows how the platform mobile rotates about its axis:

$$GT_C = A_C$$
$$= \begin{bmatrix} 1 & 2.4493e - 015 & 0 & 0 \\ -2.4493e - 015 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0.15 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(27)

Table 7 Simulation and real experimentation

Task	Performance		Comments
	Simulation ($\bar{e}$ and RMS)	Real system ($\bar{e}$ and RMS)	
1. Orientation.	40 mm and 40.16 mm	60 mm and 60.09 mm	Error due to wheel slip on the floor.
2. Approaching.	2.37 mm and 2.38 mm	6.5 mm and 6.52 mm	Two tests were performed at 0.5 m /s.
3. Manipulation.	0.050 mm and 0.050 mm	4.25 mm and 4.25 mm	The large error is due to slipping of wheels on the floor.
4. Lifting.	0.02 mm and 0.02 mm	5 mm and 5.04 mm	Due to adjustment and the weight from mobile manipulator.
5. Climbing.	0.04 mm and 0.041 mm	6.3 mm and 6.31 mm	It is due to deformation of the rear wheels and its adjustment, and to the weight of the mobile manipulator.
	8.5 mm 8.53 mm With load	16.41 mm 16.45 mm Without load	
Dynamic analysis with the CAE software	The center of mass varies in a diameter of 60 mm.	The center of mass varies in a diameter of 40 mm.	The greatest variation occurs in Z.
	The stress due to load is 14 Kpa.	The stress due to load is 7 kpa.	It was validated to the fullest extent and in the normal state of the prismatic joint.
	The λ_2 deformation is of 1.055 mm.	The λ_2 deformation is of 0.03 mm.	

According to the manual B.L.A.D.E. of Secretariat of National Defense (Mexico) the artifact manipulation error it is considered around 10 mm

b) Equation 28 is the transformation of the platform according to the parameters: $x_C = 2$, $y_C = 2$, $\lambda_{C0} = 0.15$, $\varphi_C = \frac{\pi}{4}$, $\theta_R = 2\pi$, $\theta_L = -2\pi$, $b = 0.4$, $\Delta\lambda_C = 0$

$$GT_C = A_C = \begin{bmatrix} 0.7071 & -0.7071 & 0 & 2 \\ 0.7071 & 0.7071 & 0 & 2 \\ 0 & 0 & 1 & 0.15 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (28)$$

c) Equation 29 is the transformation of the Manipulator with end effector: $x_C = 2$, $y_C = 2$, $\lambda_{C0} = 0.15$, $\varphi_C = \frac{\pi}{4}$, $\lambda_0 = 0.16$, $l_0 = 0.33$, $\theta_1 = \frac{3\pi}{4}$, $\lambda_2 = 1.4$, $\theta_3 = -\frac{\pi}{2}$, $l_3 = 0.15$, $\theta_4 = \frac{\pi}{2}$, $\theta_{C1} = \frac{\pi}{2}$, $l_{CS1} = 0.44$, $r = 0.08$, $\lambda_5 = 0.38$, $\lambda_6 = 0.25$,

$$X_M = GT_4EE_\mu$$

$$= \begin{bmatrix} 0.7071 & 0.5000 & 0.5000 & 2.8567 \\ -0.7071 & 0.5000 & 0.5000 & 2.8567 \\ 0 & -0.7071 & -0.7071 & 1.3305 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (29)$$

d) Equation 30 is the transformation when the platform is lifting: $x_C = 0$, $y_C = 0$, $\theta_{C1} = \frac{\pi}{2}$,

$$GT_C = A_C = \begin{bmatrix} 0.7071 & -0.7071 & 0 & 0 \\ 0.7071 & 0.7071 & 0 & 0 \\ 0 & 0 & 1 & 0.5200 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$(30)$$

e) Equation 31 is the transformation for climbing: $x_C = 0$, $y_C = 0$, $\lambda_{C0} = 0.15$, $\varphi_C = \frac{\pi}{4}$, $\theta_{C1} = \frac{\pi}{2}$, $\theta_{CS1} = -\frac{\pi}{2}$, $d = 0.35$, $l_{CS} = 0.33$, $l_{CS1} = 0.44$, $r = 0.10$

$$GT_{CS1} = \begin{bmatrix} 0.7071 & 0 & -0.7071 & 0 \\ 0.7071 & 0 & 0.7071 & 0 \\ 0 & -1 & 0 & 0.47 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (31)$$

Subsequently, the behavior of the mobile manipulator is simulated using (22), from which the respective errors of each area are obtained (Tables 4, 5 and 6).

In Table 7 the results of real experimentation in the mobile manipulator are shown, focused in the maximum and minimum errors according to the reference values.

In Fig. 9, it is shown the positioning test of the mobile manipulator, whereas a target was positioned
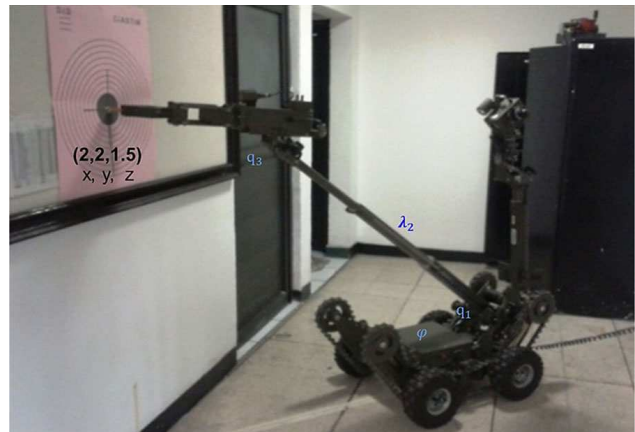

Fig. 9 Mobile manipulator in real experimentation. A set of 30 samples were carried out in order to validate simulation

at the wall localized in coordinates ($x = 2$, $y = 2$ and $z = 1.5$). In the initial setup, the robot was placed with an angle of $45°$ regarding to the wall (global coordinates) using stages 3 and 4 of the master map. The final coordinates of the end effector where established from the beginning of the experimentation.

4 Discussion

The real experimentation was done on the floor surface, which helped in the measurement of the register parameters. In Table 8, it is presented the comparison of errors of the simulations and real experimentation of 5 tasks. For each task, 30 tests were carried out,

Table 8 Summary of simulation and real experimentation errors

Comparison of simulation and real experimentation		
Tasks	Difference	
1. Orientation.	$\bar{e}$	20 mm
	RMS	19.95 mm
2. Approaching.	$\bar{e}$	4.13 mm
	RMS	4.15 mm
3. Handling.	$\bar{e}$	4.2 mm
	RMS	4.2 mm
4. Lifting.	$\bar{e}$	4.98 mm
	RMS	5.02 mm
5. Climbing.	$\bar{e}$	6.26 mm
	RMS	6.28 mm
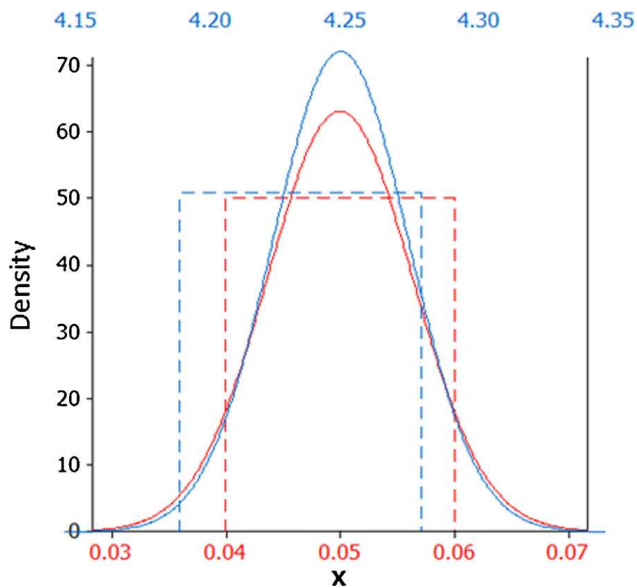
Fig. 10 Simulation and real experimentation in the manipulation task. The blue continuous line represents the normal distribution and blue doted line represents the uniform distribution, both in the real experimentation. The red continuous line represents the normal distribution and red doted line represents the uniform distribution, both in the real simulation

(according to these tests the kinematic modeling of the robot is validated).

In Table 8, it is shown the difference of errors from simulated and real experimentation from the 5 assessed tasks. Figure 10 shows the simulation results in blue color and the experimentation in red color including the media and R.M.S. errors.

5 Conclusions

A methodology for positioning the multiarticulated mobile manipulator by means of the kinematic model is defined, explained and assessed, where the use of a novel scheme to devise the homogenous transformations provides a structure for the forward kinematics. The methodology has the following advantages: (1) gives a big picture of the mechatronic design when the modeling and simulation of a mobile manipulator is developed; (2) simplifies the obtained homogenous transformation when it is required; (3) allows to determine the interaction parameters when it is necessary to consider the coupled schemes; (4) ease the kinematic modeling when any added subsystem is incorporated, in the analysis of performance index based in the error of the real operation scenarios:

The simulations has an error of 3.47 mm regarding to the references values, while the real experimentation has an error of 7.91 mm, it is an permissible error in relation with the 10 mm that is specified in the deactivation tasks [32, 33]. The maxim deformation of the manipulator with load of 10 kg was 1 mm.

The main contribuition of this work is the development of the coupled kinematic model for a wheeled mobile manipulator of 12° of freedom, also the extension of the homogeneous transformation graph that makes modular the establishing of transformation for the kinematics of mobile manipulators, and finally to propose a methodology capable to model the positioning of the mobile manipulators in real operation scenarios.

The total increment Z_c (in local coordinates) respect to the global coordinates is function of $\lambda c0$ (wheels radio) and $\Delta \lambda c$ (the slope according to the terrain shape). In order to estimate this parameter with higher precision a proximity sensor is used which is situated under the platform. The odometry of the system is based in absolute encoders. Due to this, the positioning error increases when the robot is further displaced. Future research includes using external sensors, like GPRS, to refresh the actual position, experimentation in the field, incorporate a vision system in order to detect objectives, instrumentation of the end effector in order to carry out different kinds of manipulation and the implementation of the presented modeling methodology in other mobile manipulator configurations. Furthermore, Human-robot interfaces will be studied in order to make the teleoperation of the system more intuitive [34].

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