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Fuzzy Nonprehensile Manipulation Control of a Two-Rigid-Link Object by Two Cooperative Arms

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Abstract: Motivated by the application of robots in holding and/or transferring a patient, this paper introduces the nonprehensile manipulation control algorithm for lifting up (or lowering down) a two-rigid link object with a passive joint applying two cooperative arms in a two-dimensional space. Fuzzy technique is applied for manipulation control, with high friction at contact, as it is very difficult to be done by conventional model based methods. A fuzzy controller is designed for every variable of the four dimensional position vector specifying the joint's position and links' orientations. A rule of a fuzzy controller would be like a human would do: while the friction at contact is high, "IF the reference position is far THEN move the hands quickly forward". An enhanced dynamic model of the system with high friction at contact for simulation purposes is presented. Simulation results for the manipulation control with the proposed fuzzy controllers are presented to verify the validity of the proposed control algorithm in the achievement of the manipulation motion.

Keywords: Intelligent controllers, robotics technology, systems modeling, nonprehensile manipulation control.

1. INTRODUCTION

Human interactive robotics is expected to come in direct contact with human at care facilities and/or homes in the very near future. Introduced by RIKEN-TRI collaboration center, RI-MAN (Odashima et al., 2007; Onishi et al., 2007) and RIBA, Fig. 1, are designed to grasp, lift up, hold and/or transfer a human applying their whole two-arms. In such an application, the goal is to manipulate a multi-link heavy object whose kinematics and dynamics are significant for planning its stable manipulation. Towards the more general and difficult problem of manipulating a human, this paper is concerned with a simplified one: manipulation of a two rigid link object by two cooperative arms in a two dimensional space. Manipulating a two-link object, Fig. 2, lies in the taxonomy of nonprehensile (without a form- or force-closure) manipulation (Lynch and Mason, 1999) with its many benefits such as increasing the repertoire of actions to manipulators, increasing the speed of manipulation, saving the complexity and the mass of the robot, and transferring the complexity of the robot system from the hardware (joints and actuators) to planning and control.

Many research works for different nonprehensile manipulation tasks can be found in the literature. Motion planning of a 1-DOF dynamic pitching robot throwing a ball in a horizontal plane is presented by Mori et al. (2009).

Fig. 1. RIBA holding a human

Dynamic manipulation of an object over a plate inspired by the handling of a pizza peel is presented by Higashimori et al. (2009). Motion planning and controllability for nonprehensile manipulation for throwing and catching a disc using two planar manipulators are presented by Beigzadeh et al. (2006). Carrying a polygonal shape object applying two mobile robots with nonprehensile manipulators has been presented by Gupta et al. (2003).

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So far the presented work is concerned with one-link object to be manipulated by one or two manipulators. However, multi-link object dynamic manipulation is important for its promising applications, like transferring a patient or lifting up/holding a baby by two cooperative arms. Among the few presented work for multi-link object manipulation is the research work introduced by Onishi et al. (2003); the authors applied six high speed cameras, 8 force plates and accelerometers to capture the dynamic motion behaviours of a human and simulate for virtual human robot interaction.

Importance of analyzing a real human-robot interaction has motivated authors to analyze a two link object manipulation system kinematics in Zyada et al. (2010a), and to analyze the nonprehensile static holding as well as to control the tracking lifting-up object manipulation by two-cooperative arms with a frictionless contact in Zyada et al. (2010b). For stable manipulation, not only the interaction forces are important, (like the traditional problem of cooperative control), but also the interaction location. The interaction forces are composed of both normal forces (normal to the surface of contact) and tangential friction forces (in the surface of contact which is a line in a two-dimensional case), Fig. 2. If the contact surface is frictionless and all system parameters such as the lengths and weights of the objects are exactly known, object manipulation can be controlled by conventional control methods (system-dynamics based control) as Zyada et al. (2010b) shows. However, in a real-world application where the precise knowledge of the system parameters cannot be expected to be known beforehand and the friction forces effectively exist, it is very difficult to design a controller for object manipulation by conventional model based methods.

Fuzzy technique provides a promising alternative to model and/or control physical systems that are too vague or too complicated to be modelled/controlled by conventional means. Fuzzy controllers are proposed for controlling the manipulation of a two-link object by two cooperative arms without knowledge about either the system dynamics or the friction forces at the lines of contact. In this work, friction forces are assumed to be high enough such that no-sliding would occur. The suggested formulation of a fuzzy controller is “IF (input 1 is A and input 2 is B) THEN (the control action is C)”, where A, B and C are fuzzy sets. Inputs to a fuzzy controller are the error and the error rate while the output is the arms’ motion. The position of the system is described by a 4-dimentional vector (two for joint position (x, y) and two for links’ orientations (θ_1, θ_2)), Fig. 2. In this paper, a fuzzy controller is designed for every variable independently (without the knowledge of the system dynamics) trying to track the planned trajectory of both joint position and links’ orientation.

To simulate the system behaviour with the proposed fuzzy controller, an enhanced dynamic model of the manipulation system is presented. Newton-Euler equations are applied for formulating the object dynamics; a visco-elastic model is applied for modelling the normal interaction (Zyada et al., 2010b) and a modified LuGre dynamic model of friction between two surfaces (Canudas de Wit et al., 1995) is applied for modelling the tangential interaction between the object links and the arms.

This paper is organized as follows: system description and problem formulation are presented in Section 2. Fuzzy controllers design is presented in Section 3. A dynamic model of the system for simulation is presented in Section 4 while the simulation results are presented in Section 5. Conclusions and recommendations for future work are presented in Section 6.

2. SYSTEM DESCRIPTION AND PROBLEM FORMULATION

2.1 *System Description*

A schematic diagram of the system is shown in Fig. 2. The object is composed of two rigid links, (link 1 and link 2), with a passive joint in between. The position of the passive joint, (x, y) with respect to a fixed reference frame, Σ_0 and the orientation angles of link 1, (θ_1) and link 2, (θ_2) completely define the object’s position and orientation in a two-dimensional space. The object links have masses and inertias m_1, J_1 and m_2, J_2 for link 1 and link 2 respectively. The centers of mass of link 1 and link 2, denoted by ⊕ in Fig.2, are located at $L_i, (i = 1, 2)$ from the passive joint. The object is manipulated by two arms, (arm 1 and arm 2) with r_i, $(i = 1, 2)$ being the radius of the arm. The position of arm 1 and arm 2 are denoted by $(x_{Ai}, y_{Ai}), (i = 1, 2)$ respectively. The interaction forces F_i, $(i = 1, 2)$ are acted at the contact points, (located at $\ell_i, (i = 1, 2)$ from the passive joint). Note that, F_i consists of a normal component, F_{Ni} and a tangential component, F_{Ti}. Also, it should be noted that the dynamic system with its parameters presented here are applied for simulation purposes not for controller design.

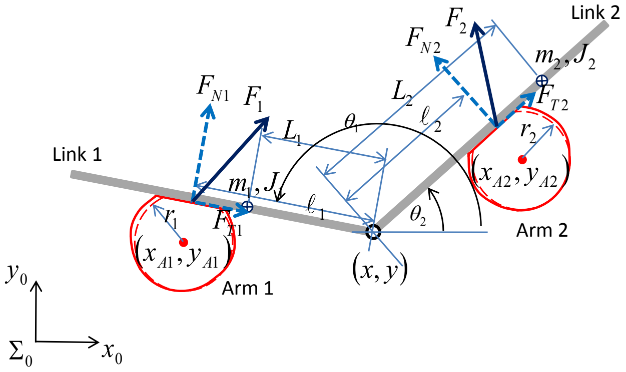


Fig. 2. Schematic diagram of the system

2.2 *Problem Formulation*

The lifting-up control problem tackled in this paper can be formulated as follows:

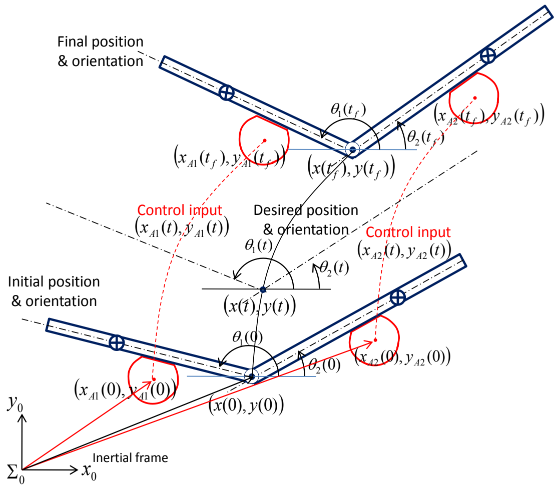


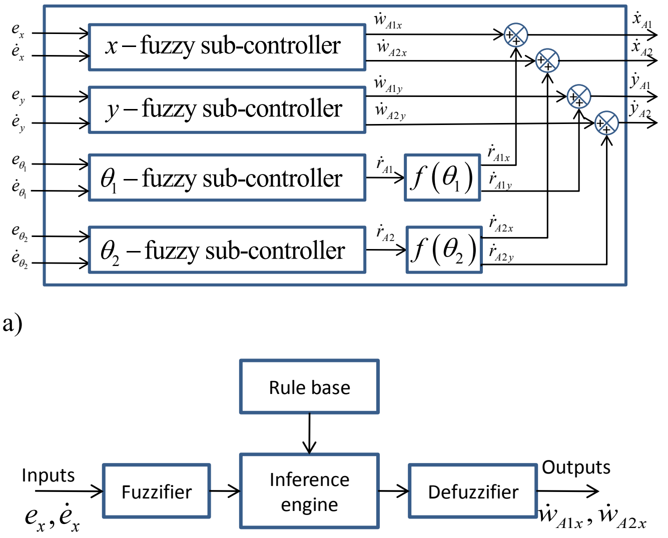
Fig. 3. Lifting-up control problem formulation

With a vague knowledge about the dynamics of the object to be manipulated and high friction at contact between the object and the arms, given the desired Lift-up trajectory which is composed of the joint position trajectory $\left(x_{ref}(t), y_{ref}(t)\right)$ and links' orientation trajectory $\left(\theta_{1ref}(t), \theta_{2ref}(t)\right)$ with $0 \le t \le t_f$; t is the time, how should be the motion trajectories of the arms $\left(x_{Ai}(t), y_{Ai}(t)\right)$, $(i=1,2)$, to track the desired Lifting-up trajectory, Fig. 3? The reference input to the controller is the desired position and orientation of object links while the controller output is the arms' motions.

3. FUZZY LOGIC CONTROLLER

Through a fuzzy controller, it is aimed to emulate a human in controlling manipulation of an object applying two cooperative arms. Manipulation control of object position by a human can be expressed as: If there is no sliding and the difference between the object reference position and the object current position is big (say in positive x-direction) then move the arms a big motion in the positive x-direction. A fuzzy logic controller is designed to control the two-link object manipulation. The contact at the interaction points of the manipulated object and the robot arms are assumed to be of the rolling type, (i.e. the friction forces are high enough such that there is no relative sliding).

Let the vector q denote the object position $q := \left(x, y, \theta_1, \theta_2\right)^T$, the vector p denote arms positions $p := \left(x_{A1}, y_{A1}, x_{A2}, y_{A2}\right)^T$ and q_{ref} denote the desired lift up trajectory $q_{ref} := \left(x_{ref}, y_{ref}, \theta_{1ref}, \theta_{2ref}\right)^T$. The motion of manipulated object q can be controlled through motions of the manipulating arms p. The fuzzy logic controller is designed with error e, $e(t) := q_{ref}(t) - q(t)$ and the error rate $\dot{e}$ being its inputs while $\dot{p}$ is its output, Fig. 4a. The fuzzy logic controller is composed of four fuzzy sub-controllers, one for each variable of the position vector q. The inputs and output for each sub-controller are shown in Fig. 4a, where we express the elements of e as $e = \left(e_x, e_y, e_{\theta 1}, e_{\theta 2}\right)^T$ in order to make physical meaning clearer. As an example, you can see that the fuzzy logic sub-controller of x has two inputs $e_x, \dot{e}_x$ (i.e. error and error rate of the position variable x) and two outputs $\dot{w}_{A1x}, \dot{w}_{A2x}$, (i.e. the velocity components by which the manipulating arms should move in x-direction), Fig. 4b. The input-output structure of the fuzzy logic of y is similar to that of x. On the other hand, the fuzzy logic controller of θ_1 has two inputs $e_{\theta 1}, \dot{e}_{\theta 1}$ (i.e. error and error rate of the angular position variable θ_1) and one output $\dot{r}_{A1}$ (the velocity component by which arm 1 should move in normal direction to the line of contact between link 1 and arm 1). θ_2 has the same logic structure as θ_1. The definition of sub-controllers outputs, (the arms' velocity components in different directions), are shown in Figure 5.



a)

b)

Fig. 4. Fuzzy logic controller; a) detailed input/output of sub-controllers; b) Mamdani fuzzy controller in x-direction

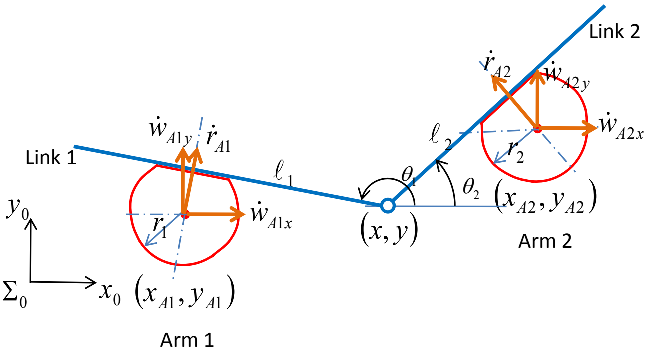


Fig. 5. Sub-controllers' outputs.

The sub-controllers' outputs for the angular position variables , (θ_1, θ_2) , $\dot{r}_{Ai}$ $(i = 1,2)$ can be expressed as two Cartesian components, $\dot{r}_{Aix}$ and $\dot{r}_{Aiy}$ $(i = 1,2)$, in x and y directions respectively, as follows:

$$\begin{aligned} \dot{r}_{Aix} &= \dot{r}_{Ai} \cos\left(\theta_i + (-1)^i \frac{\pi}{2}\right) \\ \dot{r}_{Aiy} &= \dot{r}_{Ai} \sin\left(\theta_i + (-1)^i \frac{\pi}{2}\right) \end{aligned} \tag{1}$$

The net output from the fuzzy controller, $\dot{p}$, $\dot{p} := (\dot{x}_{A1}, \dot{y}_{A1}, \dot{x}_{A2}, \dot{y}_{A2})^T$ (i.e. arms' velocity components), are the summation of the outputs from the sub-controllers, Fig. 4a. They can be expressed as:

$$\left.\begin{aligned} \dot{x}_{Ai} &= \dot{w}_{Aix} + \dot{r}_{Aix} \\ \dot{y}_{Ai} &= \dot{w}_{Aiy} + \dot{r}_{Aiy} \end{aligned}\right\} (i = 1,2) \tag{2}$$

The control input to the plant, (the arms' position), p can be obtained as the integration of arms' velocities $\dot{p}$, so that:

$$p = \int \dot{p}(t) dt \tag{3}$$

Mamdani type fuzzy controller is chosen to design each fuzzy sub-controller, like that shown in Fig. 4b for controlling object manipulation in x-direction. Triangular symmetric membership functions like that shown in Fig. 6 (for sub-controller in x-direction) are applied to fuzzify and defuzzify all input and output variables. L, B, M, S and Z stands for large, big, medium, small and zero respectively while the modifiers N and P stands for negative and positive respectively.

The fuzzy logic controller is designed as a PI (proportional plus integral)-like controller. The fuzzy control rules of the variable x-controller are listed in Table 1 as an example of the designed controllers. A rule of the fuzzy rule table would be stated as: "**IF** the error e_x is NS and the error rate $\dot{e}_x$ is NM" **THEN** "the arms' velocities $\dot{w}_{A1x}$ and $\dot{w}_{A2x}$ are NB.

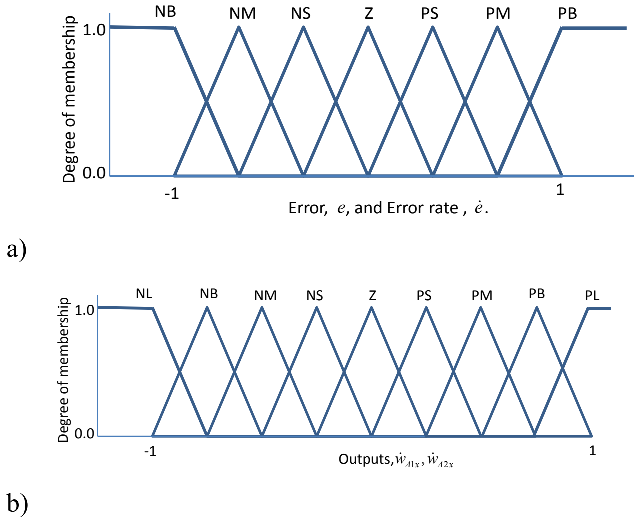


Fig. 6. Normalized input-output membership functions: a) inputs: error and error rate; b) output: arms' velocity components

Table 1. Rule base table of PI-like fuzzy controller

Outputs: $\dot{w}_{A1x}$, $\dot{w}_{A2x}$		Input $\dot{e}_x$						
		NB	NM	NS	Z	PS	PM	PB
Input e_x	NB	NL	NL	NL	NB	NM	NS	Z
	NM	NL	NL	NB	NM	NS	Z	PS
	NS	NL	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PL
	PM	NS	Z	PS	PM	PB	PL	PL
	PB	Z	PS	PM	PB	PL	PL	PL

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This rule can be interpreted as: if the difference between the reference position and the position is small (in negative x-direction) and the rate of change of that difference is medium in negative direction then move the arms with a big speed in the negative x-direction.

It should be noted that the presented PI-like fuzzy controller is designed without the exact knowledge about the system dynamic model in contrast to a conventional controller in which the system model is proposed to be known.

4. SYSTEM DYNAMICS

In this section, the system dynamics (for the purpose of simulation) is introduced. The object dynamic model is first introduced followed by the contact model and the kinematic relations.

4.1 Object Dynamic Model

Using the position vector $q := (x, y, \theta_1, \theta_2)^T$ and applying Newton-Euler equations of motion, the dynamics of the object can be described as:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = B(q,\ell)u \tag{4}$$

where:

$$M(q) := \begin{bmatrix} m_1 + m_2 & 0 & -m_1 L_1 \sin\theta_1 & -m_2 L_2 \sin\theta_2 \\ 0 & m_1 + m_2 & m_1 L_1 \cos\theta_1 & m_2 L_2 \cos\theta_2 \\ -m_1 L_1 \sin\theta_1 & m_1 L_1 \cos\theta_1 & J_1 + m_1 L_1^2 & 0 \\ -m_2 L_2 \sin\theta_2 & m_2 L_2 \cos\theta_2 & 0 & J_2 + m_2 L_2^2 \end{bmatrix},$$

$$C(q,\dot{q}) := \begin{bmatrix} 0 & 0 & -m_1 L_1 \dot{\theta}_1 \cos\theta_1 & -m_2 L_2 \dot{\theta}_2 \cos\theta_2 \\ 0 & 0 & -m_1 L_1 \dot{\theta}_1 \sin\theta_1 & -m_2 L_2 \dot{\theta}_2 \sin\theta_2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$G(q) := [0 \quad (m_1 + m_2) g \quad m_1 g L_1 \cos\theta_1 \quad m_2 g L_2 \cos\theta_2]^T,$$

$$B(q,\ell) := \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -\ell_1 \sin\theta_1 & \ell_1 \cos\theta_1 & 0 & 0 \\ 0 & 0 & -\ell_2 \sin\theta_2 & \ell_2 \cos\theta_2 \end{bmatrix}$$

and $u := \begin{bmatrix} u_1^T & u_2^T \end{bmatrix}^T$, g is the gravitational acceleration. u_1 and u_2 can be described as:

$$u_1 := \begin{bmatrix} \sin\theta_1 & -\cos\theta_1 \\ -\cos\theta_1 & -\sin\theta_1 \end{bmatrix} \begin{bmatrix} F_{N1} \\ F_{T1} \end{bmatrix}; \quad u_2 := \begin{bmatrix} -\sin\theta_2 & \cos\theta_2 \\ \cos\theta_2 & \sin\theta_2 \end{bmatrix} \begin{bmatrix} F_{N2} \\ F_{T2} \end{bmatrix}$$

where F_{Ni}, F_{Ti} are the normal and tangential force components at the points of contact of link i with arm i, $(i=1,2)$. Note that ℓ_1, ℓ_2 in the matrix $B(q,\ell)$ are functions of q and x_{Ai}, y_{Ai} as follows:

$$\left.\begin{aligned} \ell_1 &= -(x - x_{A1})\cos\theta_1 - (y - y_{A1})\sin\theta_1 \\ \ell_2 &= (x_{A2} - x)\cos\theta_2 - (y_{A2} - y)\sin\theta_2 \end{aligned}\right\} \qquad (5)$$

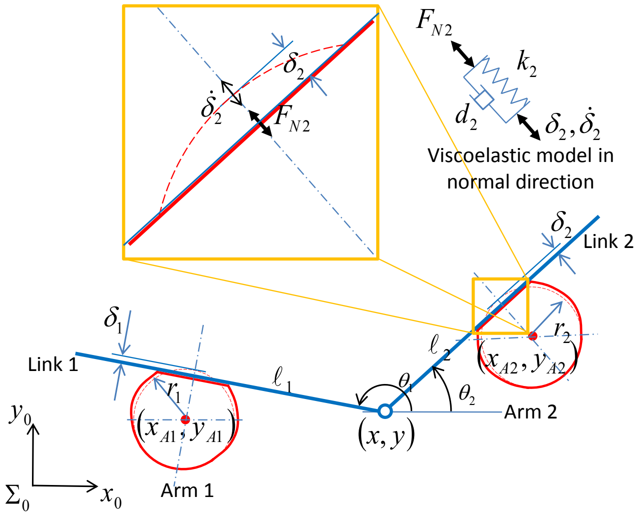

Fig. 7. Visco-elastic model of contact in normal direction

4.2 *Contact Model*

The interaction behaviour between a link and the arm in the normal direction at contact is modelled as a visco-elastic model, Fig. 7, as follows:

$$F_{Ni} = \begin{cases} k_i \delta_i + d_i \dot{\delta}_i & \text{for } \delta \geq 0 \\ 0 & \text{for } \delta < 0 \end{cases} \qquad (6)$$

where F_{Ni}, $(i=1,2)$ is the normal interaction force; k_i is spring constant; d_i a viscosity coefficient; and δ_i is a radial deformation in the direction normal to the contact plane while $\dot{\delta}_i$ is its time-rate of change.

Based on LuGre dynamic model of friction between two surfaces (Canudas de Wit et al., 1995; Canudas de Wit, 1999), the interaction behaviour in the tangential direction to contact points can be expressed as a dynamic friction model taking the elastic and damping behaviour of the material into account as follows:

$$\left.\begin{aligned} \dot{z}_i &= -v_i - \frac{|v_i|}{f(v_i)} z_i \\ F_{Ti} &= \sigma_{0i} z_i + \sigma_{1i} \dot{z}_i - \sigma_{2i} v_i \operatorname{sgn}(v_i) \\ \sigma_{0i} f(v_i) &= \left(\mu_{Ci} + (\mu_{Si} - \mu_{Ci}) e^{-|v_i / v_{si}|^{1/2}} \right) F_{Ni} \end{aligned}\right\} \qquad (7)$$

where z_i, $(i=1,2)$ is the average deflection of bristles of two materials at contact i, v_i is the relative tangential velocity between the object and arm at contact i, F_{Ti} is the tangential interaction forces, σ_{0i} is the stiffness and σ_{1i} is the damping coefficient at contact i which are mainly dependent on arms coating material properties, σ_{2i} is the viscous relative damping coefficient, μ_{Ci} and μ_{Si} are the Coulomb friction and stiction force coefficients at contact i respectively, v_{si} is the Stribeck velocity at contact i.

4.3 *Kinematic relations*

δ_i, Fig. 7, of equation (6) and v_i of equation (7) can be obtained from the following kinematic relations:

$$\left.\begin{aligned} \delta_1 &= r_1 - (x - x_{A1})\sin\theta_1 + (y - y_{A1})\cos\theta_1 \\ \delta_2 &= r_2 - (x_{A2} - x)\sin\theta_2 + (y_{A2} - y)\cos\theta_1 \end{aligned}\right\}, \qquad (8)$$

$$\left.\begin{aligned} v_1 &= -(\dot{x} - \dot{x}_{A1})\cos\theta_1 - (\dot{y} - \dot{y}_{A1})\sin\theta_1 \\ v_2 &= (\dot{x} - \dot{x}_{A2})\cos\theta_2 + (\dot{y} - \dot{y}_{A2})\sin\theta_2 \end{aligned}\right\} \qquad (9)$$

where $\dot{x}_{Ai}, \dot{y}_{Ai}$; $(i=1,2)$, are the arms' velocity components.

5. SIMULATION RESULTS

The manipulating system of a two link object with a fuzzy controller, Fig. 8, with system parameters shown in Table 2 is applied for simulation. The initial contact positions of arms and links are assumed to be known as the equilibrium position before manipulation (Zyada et al., 2010b). It is assumed that the desired Lift-up trajectory $q_{ref} := (x_{ref}, y_{ref}, \theta_{1ref}, \theta_{2ref})^T$ is given such that:

$$\begin{cases} q_{ref}(0) = (0,0,130,30)^T \\ q_{ref}(t) = (0.1,0.2,160,45)^T \quad \text{for} \quad t \geq 3 \end{cases}$$

and $q_{ref}(t)$ from $t=0$ to $t=3$ is a 5th power polynomial function of t.

The simulation is carried out applying MATLAB Simulink and its fuzzy toolbox, where implication and aggregation are treated as minimum and maximum operations respectively

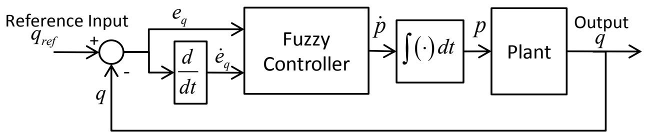

Fig. 8. Closed loop system with fuzzy controller

Table 2. Physical parameters of the system

Symbol		$i=1$	$i=2$
Object	m_i [Kg]	15	35
	J_i [Kgm^2]	1	1
	L_i [m]	0.24	0.352
	r_i [m]	0.1	0.1
Normal contact	k_i [N/m]	10^5	10^5
	d_i [Ns/m]	10^3	10^3
Tangential contact	σ_0 [N/m]	10^5	10^5
	σ_1 [Ns/m]	10^3	10^3
	σ_2 [Ns/m]	0.001	0.001
	μ_S	0.9	0.9
	μ_C	0.5	0.5
	v_s [m/s]	0.01	0.01

and the centroid calculation is applied for defuzzification.

Three sets of simulations are carried out and their results are presented. The first set is shown in Fig. 9 for the system with the designed fuzzy controller as presented in the previous sections. The second set is shown in Fig. 10 for the system with an external load disturbance applying the same fuzzy controller. The third set is presented in Fig. 11 to check the robustness of the control system against the changeable system parameters, like stiffness and damping coefficients at contact.

Figure 9a shows the simulation results of object position and links orientation. It shows the good agreement of the output position/orientation compared to the reference trajectories. Figure 9b shows the arms' positions (i.e. the control action applied to the plant to track the desired position and orientation). Figure 9c shows the interaction forces between the links and arms in both normal and tangential directions. Fig. 9d shows the fuzzy controller output, that is the arms'

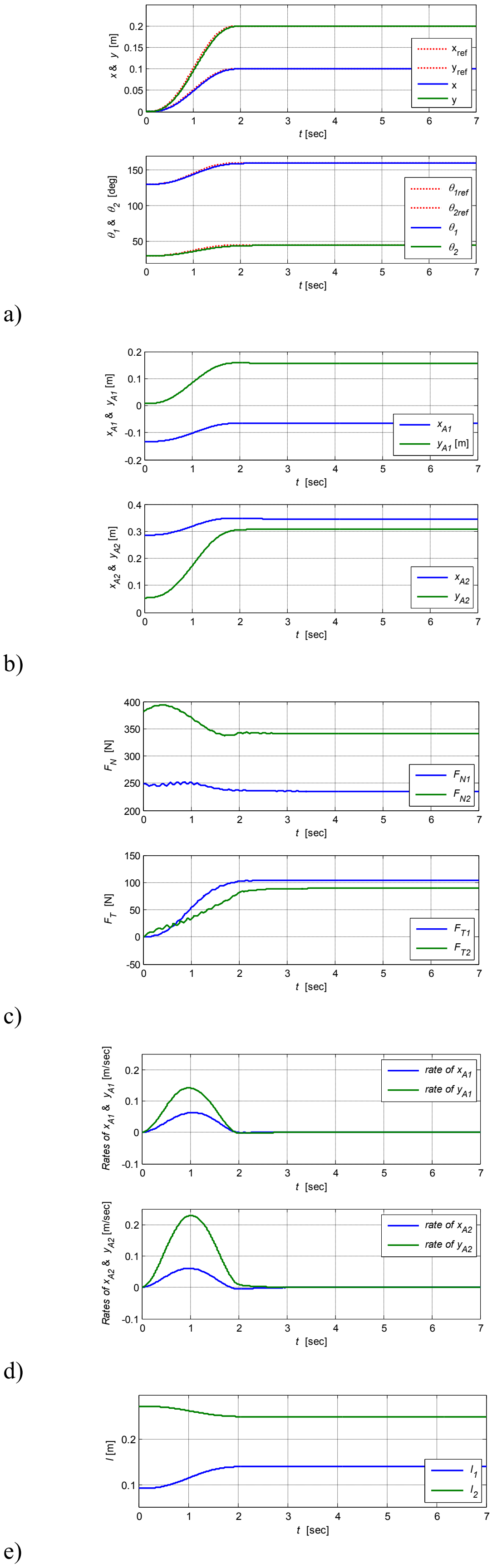

Fig. 9. Simulation results; a) position & orientation, b) arms' positions, c) forces at contact, d) controller output, e) lengths between the joint and points of contact.

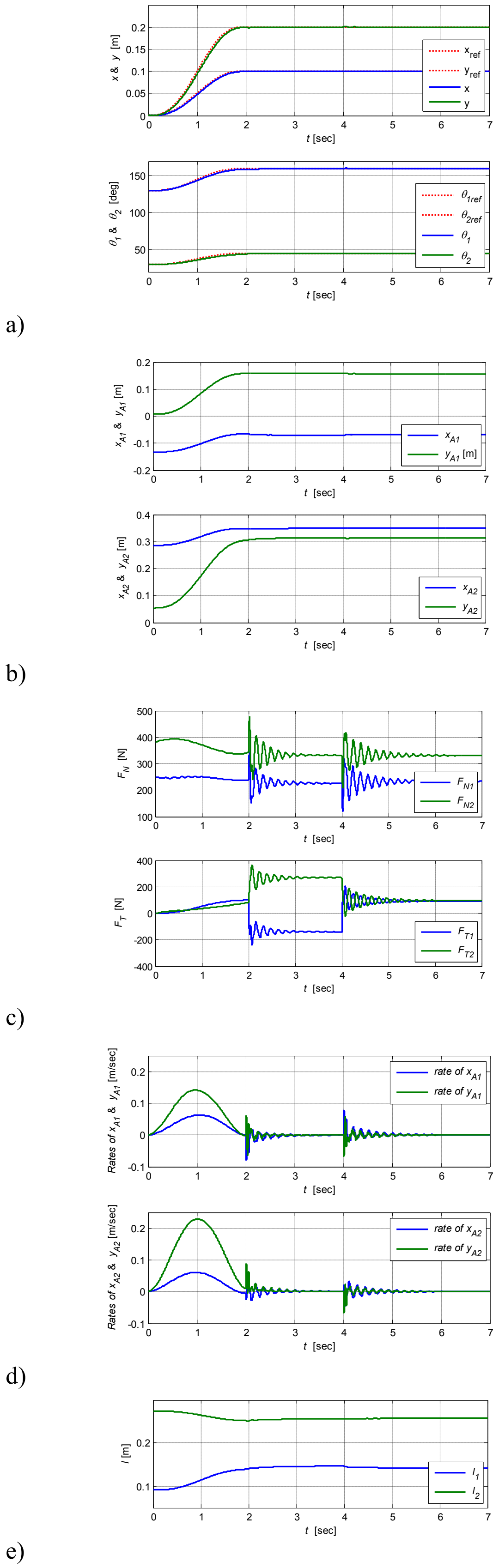

Fig. 10. Simulation results with external force disturbance; a) position & orientation, b) arms' positions, c) forces at contact, d), controller output, e) lengths between the joint and points of contact.

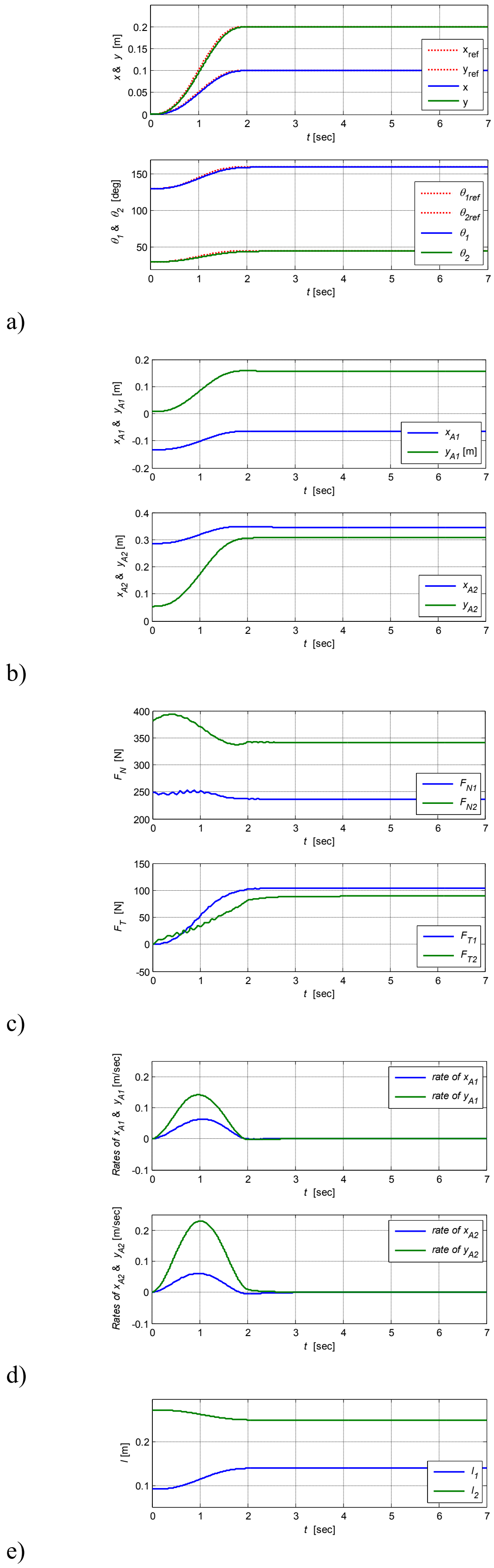

Fig. 11. Simulation results with different tangential stiffness and damping coefficients; a) position & orientation, b) arms' positions, c) forces at contact, d), controller output, e) lengths between the joint and points of contact.

velocity components. Figure 9e shows the length between the joint and the contact points on both links. It is referred as $\ell_i, (i=1,2)$ (Section 2). It should be noted that the change in lengths is due to rolling motion between links and arms at contact points.

Figure 10 shows the simulation results with the application of external force disturbance of 10 $\mathrm{kgf}\,(10\mathrm{x}9.81\ \mathrm{N})$ in *x*-direction and 20 $\mathrm{kgf}\,(20\mathrm{x}9.81\ \mathrm{N})$ in negative *y*-direction, at the joint, between 2 and 4 seconds. The figure shows the effectiveness of the fuzzy controller in tracking the reference trajectory even though the system is under external load disturbance. Figure 11 shows the simulation results for the system with stiffness and damping coefficients at contact in tangential directions decreased by 10% of the tabulated value in Table 2. This figure compared to Fig. 9 shows the robustness of the fuzzy controller against the changeable system parameters at contact.

To be applied to RIBA, it is planned to build a 2D manipulating system and check this controller experimentally.

6. CONCLUSIONS AND RECOMMENDATIONS

In this paper, fuzzy control of a two-rigid-link object applying two cooperative arms is presented which is very important for future nonprehensile manipulation tasks such as transferring a patient from a place to another applying a nursing robot. A fuzzy controller is designed for the manipulation task, (with high friction at contact between the arms and links), which is difficult to be done by conventional model based methods. A controller is designed for every variable of the object's position vector without the need to know or understand the dynamics of the manipulated object. A dynamic model of the system is presented for the purpose of simulation. Simulation results for system with a fuzzy controller are presented which show the effectiveness and the promise of the proposed approach.

Extension of this research work would include spatial motion control of multi-link object as well as the design of a self-regulating or adaptive fuzzy controller.

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