Modified Position-Force Control for a Manipulator Geometrically Constrained by Round Obstacles

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Abstract:
This paper addresses the problem of position-force control for robot manipulators under geometric endpoint constraints defined as round obstacles. Considerations are based on hybrid position-force control and use modified Arimoto algorithm with the principle of "orthogonalisation". To achieve so-called joint space orthogonalisation, where motion signals are orthogonal to force vectors and the direction selection is performed in the joint space, projection matrix is utilized. The convergence of tracking and force errors is proved.

Keywords: *manipulator, position-force control, principle of orthogonalisation, hybrid control*

1. Introduction

Over the years, the use of robots has been increasing, especially in industry. Many of the simple tasks may need only trajectory control. In such a case the robot end-effector is moved only along a desired time trajectory and position control is sufficient to achieve a goal. However, in order to perform many more complex tasks, such as assembly of parts, manipulation of tools, washing a window and the other, the robot end-effector must come into physical interactions with its environment. Successful execution of those tasks requires the approach considering the force of the contact and different control strategies.

Tasks that require force control may vary and include the situation where applying a controlled force is needed for a manufacturing process (e.g. deburring and grinding), or pushing an external object using a controlled force is needed, or dealing with geometric uncertainty (e.g. in assembly) [5]. In the case of tasks assuming the possibility of contact of the manipulator with the environment, three phases can be distinguished [20, 21]:

1) approaching phase – free movement,
2) transition phase – free movement with expected contact,
3) contact phase – exerting a given force.

The first phase involves approaching the object and represents the motion in a collision-free space. Therefore, positional control algorithms can be used for its implementation. The second phase is the transition from free movement to contact with the environment. This phase may be impacted by surroundings, therefore the control here is the most complex. Forces that may occur during a collision are usually not fully known. In the control process, it is necessary to manage position and force simultaneously. If the contact does not occur, the control system tries to reach the desired position or speed. However, in the case of contact, the set trajectory must be modified accordingly. The complication in the control process may be the fact that in the result of the contact, an unexpected manipulator's behaviour may occur. In such a case, the manipulator may fall into vibrations or oscillations [21]. The last phase of control requires constant contact with the surroundings. Depending on the task, it may be necessary to exert a force with a certain value with a simultaneous change in the position of the manipulator.

Considering manipulator's interaction with the environment, the ability to model the environment, in which the robot operates, plays an important role. The type of environment and the degree of its familiarity largely determine the choice of the control algorithm. An approach in which the environment is well-known is shown, among others at work [4] and [10], while dealing with limited knowledge about the environment is presented in [6, 7, 11, 17] and [16]. In this paper we assume that environment is well known.

For performing a class of tasks entailing the manipulator's contact with the environment, force and compliance control are fundamental strategies [9, 18, 22]. In this article we will present a basic strategy for dealing with geometric constraints imposed by the robot environment – hybrid position-force control.

For the first time the idea and scheme of hybrid motion-force control was proposed by Craig and Raibert [3] and based on decoupling of motion control and force control: motion – in directions without constrains, exerted force – in constrained directions. The problem was the kinematic instability of proposed hybrid position-force control scheme, which was connected with position control part. Fisher and Mujtaba [8] showed that kinematic instability is a result of an incomplete and inappropriate formulation of the problem, and proposed correct formulation of hybrid position-force control. Over the years, many various schemes have been proposed for such control systems. An insightful description of them can be found in [15] and a new review of notable interest is in [14].

Hybrid position-force control scheme is based on capability to provide both motion and force control which do not interact with each other. It is necessary to select directions where motion can be executed (position control) and other directions, where is the possibility to exert forces on a contact surface. Decoupling of motion and force control is fundamental and can be achieved in various ways depending on e.g. chosen space. Schemes introduced in [3, 8] are based on selection matrix used for decoupling between motion and force through an appropriate selection of directions in the Cartesian space. Another approach can be found in [1, 2], where projection matrix is used to achieve so-called joint space orthogonalisation. Hence motion signals are orthogonal to force vectors and the selection is performed in the joint space.

The result of comparison between classic hybrid control and modified Arimoto algorithm for a flat obstacle, were presented by authors before in [12]. In this article we present a modified hybrid position-force control algorithm based on joint space orthogonalisation, to achieve the following goal: position-force control for manipulator with round obstacles. Considerations involve mathematical proof of the position and force errors convergence. Results of simulation experiments are also presented.

In section 2 we present some preliminary information about manipulator dynamics under constraint. Next, in section 3 the control problem statement is given. Section 4 is devoted to the study of joint-space orthogonalisation. Afterwards, in section 5, the control law is stated and proved. Results of simulations are presented in section 6. Section 7 contains a brief summary and conclusions.

2. Robot Dynamics Under Constraint

Suppose that the model of manipulator is fully known and the manipulator endpoint is in physical contact with rigid surface described as holonomic constraint

$$\Phi(p) = 0. \tag{1}$$

where $p = (x, y, z)^T$ denotes the Cartesian (task) coordinates. Then the robot dynamics is described in terms of joint coordinates $q = (q_1, ..., q_n)$ in the following form

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + D(q) = u + J_{\phi n}^T f, \tag{2}$$

where the left hand side of expression describes dynamics of the manipulator with following elements

- $q, \dot{q}, \ddot{q} \in R^n$ – vector of joint positions, velocities and accelerations,
- $M(q)$ – symmetrical, positive definite inertia matrix,
- $C(q, \dot{q})$ – matrix of Coriolis and centripetal forces,
- $D(q)$ – vector of gravitational forces.

The right hand side of (2) includes control vector u and expression $J_{\phi n}^T f$ which represents the contact force exerted at joints where $J_{\phi n}$ is normalized vector J_ϕ defined as follows

$$J_{\phi n} = \frac{J_\phi}{\parallel J_\phi \parallel}$$

and

$$J_\phi = \frac{\partial \Phi}{\partial p} \cdot \frac{\partial p}{\partial q} = A(p) J_a(q),$$

where J_a is Jacobi matrix.

3. Control Problem Statement

As it was mentioned in introduction, in this paper we address the following control problem: fixed-based manipulator with fully known dynamics should track desired trajectory $p_d(t)$ on the surface of the round obstacle with simultaneously exerting desired force f_d in the direction orthogonal to the obstacle superficies.

We will make the following assumptions:

- an obstacle is fully-known and completely rigid – given as holonomic constraint and defined in Cartesian coordinates,
- the manipulator's end-effector is in physical contact with the obstacle,
- desired trajectory $p_d(t)$ is C^2 class and is defined on the surface of the obstacle in Cartesian space.

To realize such a task, it is necessary to define a control law which has a hybrid structure: directions of position and position-force control are orthogonal.

4. Joint-space Orthogonalisation

Let's assume that both desired trajectory $q_d(t)$ and force $f_d(t)$, are given in joint space. Moreover, assume that the velocity signal $\dot{q}(t)$, position signal $q(t)$ and momentum signal $F(t)$ given as

$$F(t) = \int_0^t f(\tau) d\tau, \tag{3}$$

can be measured and used in real-time. Then let us introduce so-called "nominal reference" signal defined by expression

$$\dot{q}_r = Q(q)(\dot{q}_d - \Lambda e_q) + \beta J_{\phi n}(q) e_F, \tag{4}$$

where

- $e_q = q - q_d$ denotes position error in joint coordinates,
- $\Lambda > 0$ and $\beta \geq 0$ are constants,
- $e_F = F - F_d$ denotes momentum signal error and $F_d = \int_0^t f_d(\tau) d\tau$,
- $Q(q) \in R^{n \times n}$ is projection matrix defined by

$$Q(q) = I_n - J_{\phi n}^T(q) J_{\phi n}(q). \tag{5}$$

Matrix $Q(q)$, defined by (5), projects vectors in joint space onto the plane tangent to the surface $\Phi(p(q)) = 0$ at point q. Holonomic constraint $\Phi(p(q)) = 0$ is fulfilled as long as the manipulator endpoint is in physical contact with the surface. It holds that

$$J_{\phi n}(q)\dot{q} = 0, \tag{6}$$

and also ensures that the following equations are also satisfied

$$Q(q)\dot{q} = \dot{q}, \quad Q(q) J_{\phi n}^T(q) = 0. \tag{7}$$

The difference between current velocity $\dot{q}$ and nominal reference $\dot{q}_r$ is called sliding variable s

$$s = \dot{q} - \dot{q}_r. \tag{8}$$

Since nominal reference trajectory is given by equation (4) and also (7) is satisfied, the following decomposition of the sliding variable (8) can be made

$$\begin{aligned} s &= \dot{q} - \dot{q}_r = Q(q)(\dot{e}_q + \Lambda e_q) - \beta J_\Phi^T(q) e_F \\ &= s_0 + s_1, \end{aligned} \tag{9}$$

where $\dot{e}_q = \dot{q} - \dot{q}_d$ – velocity error in joint space, $s_0 = Q(q)(\dot{e}_q + \Lambda e_q)$, and $s_1 = \beta J_\Phi^T(q) e_F$. We conclude from (7) that signal s_0 is orthogonal to the signal s_1

$$\begin{aligned} s_0^T s_1 &= -(\dot{e}_q + \Lambda e_q)^T Q_\phi \beta J_{\phi n}^T e_F \\ &= -\beta(\dot{e}_q + \Lambda e_q)^T \underbrace{Q_\phi J_{\phi n}^T}_{=0} e_F = 0. \end{aligned} \tag{10}$$

Hence, nominal reference signal (4) is also composed of two parts which are orthogonal to each other. According to [1] and [2] this design concept is called "joint-space orthogonalisation".

5. Main Result – Control Law

For the manipulator defined by equation (2) modified version of Arimoto control algorithm [1] has been chosen as the control law, which is defined by

$$\begin{aligned} u =& M(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + D(q) \\ &- K_d(\dot{e}_q + \Lambda e_q) - J_\Phi^T(q)(f_d - \gamma e_F), \end{aligned} \tag{11}$$

where $K_d = K_d^T > 0, \gamma > 0$ – regulation parameters of the controllers. Nominal reference signal $\dot{q}_r$ is defined like before as (4). Comparing to original control law proposed by Arimoto, additional term $-K_d(\dot{e}_q + \Lambda e_q)$ was added to improve algorithm convergence. And furthermore, different proof of the position and force errors convergence is presented.

5.1. Proof of the Position and Force Errors Convergence

Substituting control law (11) into system (2) we obtain the closed-loop system dynamics

$$\begin{aligned} M\ddot{q} + C\dot{q} + D =& J_{\phi n}^T f + M\ddot{q}_r + C\dot{q}_r + D - K_d s \\ &- J_{\phi n}^T (f_d - \gamma e_F). \end{aligned}$$

The above expression may be written as

$$M(\ddot{q} - \ddot{q}_r) + C(\dot{q} - \dot{q}_r) + K_d s = J_{\phi n}^T(\dot{e}_F + \gamma e_F) \tag{12}$$

and next, using the definition of sliding variable (8), we can present (12) in the following form

$$M\dot{s} + Cs + K_d s = J_{\phi n}^T(\dot{e}_F + \gamma e_F). \tag{13}$$

For the closed-loop system (13) we propose following Lyapunov-like function

$$V(s, e_F) = \frac{1}{2} s^T M(q) s + \frac{1}{2}\beta e_F^2,$$

which is non-negatively defined. We compute time derivative of V along solutions of the closed-loop system (13)

$$\dot{V} = s^T M(q)\dot{s} + \frac{1}{2} s^T \dot{M}(q) s + \beta e_F \dot{e}_F, \tag{14}$$

what can be rewritten as

$$\begin{aligned} \dot{V} &= s^T(-Cs - K_d s + J_{\phi n}^T(\dot{e}_F + \gamma e_F)) \\ &\quad + \frac{1}{2} s^T \dot{M}(q) s + \beta e_F \dot{e}_F \\ &= -s^T K_d s + s^T J_{\phi n}^T(\dot{e}_F + \gamma e_F) + \beta e_F \dot{e}_F \\ &= -s^T K_d s + (s_0^T + s_1^T) J_{\phi n}^T(\dot{e}_F + \gamma e_F) \\ &\quad + \beta e_F \dot{e}_F \\ &= -s^T K_d s + s_0^T J_{\phi n}^T(\dot{e}_F + \gamma e_F) \\ &\quad + s_1^T J_{\phi n}^T(\dot{e}_F + \gamma e_F) + \beta e_F \dot{e}_F \\ &= -s^T K_d s + (\dot{e}_q + \Lambda e_q)^T Q_\phi^T J_{\phi n}^T(\dot{e}_F + \gamma e_F) \\ &\quad - \beta e_F J_{\phi n} J_{\phi n}^T(\dot{e}_F + \gamma e_F) + \beta e_F \dot{e}_F. \end{aligned} \tag{15}$$

From the conditions (7), it is known that $Q_\phi = Q_\phi^T$ and $Q_\phi J_{\phi n}^T = 0$. Therefore, the second expression in derivative (15) is equal zero. Moreover, since $J_{\phi n} J_{\phi n}^T = 1$, it follows that

$$\begin{aligned} \dot{V} &= -s^T K_d s - \beta e_F(\dot{e}_F + \gamma e_F) + \beta e_F \dot{e}_F \\ &= -s^T K_d s - \beta\gamma e_F^2. \end{aligned} \tag{16}$$

We conclude from the properties of quadratic forms that the following inequality is satisfied:

$$s^T K_d s \geq \lambda_{min}(K_d) s^T s, \qquad \lambda_{min}(K_d) > 0. \tag{17}$$

After multiplying both sides of the equation (17) by (-1) and substituting into derivative of Lapunov function V (16) we get

$$\begin{aligned} \dot{V} &\leq -\lambda_{min}(K_d) s^T s - \beta\gamma e_F^2 \\ &= -\lambda_{min}(K_d)(s_0^T + s_1^T)(s_0 + s_1) - \beta\gamma e_F^2 \\ &= -\lambda_{min}(K_d)(s_0^T s_0 + s_0^T s_1 + s_1^T s_0 + s_1^T s_1) \\ &\quad - \beta\gamma e_F^2. \end{aligned} \tag{18}$$

Since it is shown in (10) that signals s_0 and s_1 are orthogonal, consequently we can rewrite equation (18) as follows

$$\begin{aligned} \dot{V} \leq& -\lambda_{min}(K_d) \parallel s_0 \parallel^2 - \lambda_{min}(K_d) \parallel s_1 \parallel^2 \\ &- \beta\gamma e_F^2 \leq 0 \end{aligned} \tag{19}$$

Finally, we get that stable equilibrium of the system (13) is $(s_0, s_1, e_F) = (0, 0, 0)$, which implies following properties

$$s_0 = \dot{e}_q + \Lambda e_q \to 0 \implies e_q \to 0 \tag{20}$$

along with convergence to zero. This ends the proof.

6. Simulations

The simulations have been done using the MATLAB package and the SIMULINK toolbox. As an object of simulations we have taken RTR manipulator, presented in fig.1.

Links of the RTR manipulator have been modeled as homogenous sticks with length equal to $l_2 = 0.9$m, $l_3 = 1$m, and masses $m_2 = 20$kg, $m_3 = 20$kg. Dynamics of manipulator is given by the equation (2) with elements equal to

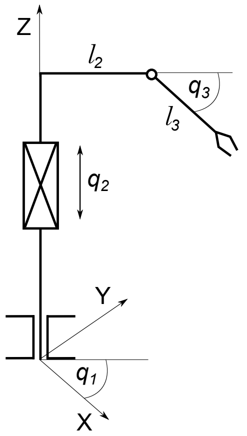

Fig. 1. Scheme of modelled RTR manipulator

- M – symmetric positive definite inertia matrix

$$M(q) = \begin{bmatrix} M_{11} & 0 & 0 \\ 0 & M_{22} & M_{23} \\ 0 & M_{23} & M_{33} \end{bmatrix}, \qquad (21)$$

$M_{11} = \frac{1}{3}m_2 l_2^2 + m_3(l_2^2 + \frac{1}{3}l_3^2 \cos^2 q_3 + l_2 l_3 \cos q_3)$,
$M_{22} = m_2 + m_3$,
$M_{23} = \frac{1}{2}m_3 l_2 l_3 \cos q_3$,
$M_{33} = \frac{1}{3}m_3 l_3^2$,

- C – matrix of centripetal and Coriolis forces

$$C(q, \dot{q}) = \begin{bmatrix} C_{11} & 0 & C_{13} \\ 0 & 0 & C_{23} \\ C_{31} & 0 & 0 \end{bmatrix}, \qquad (22)$$

$C_{11} = \dot{q}_3(-\frac{1}{2}m_3 l_2 l_3 \sin q_3 - \frac{1}{3}m_3 l_3^2 \sin q_3 \cos q_3)$,
$C_{13} = -\dot{q}_1(\frac{1}{2}m_3 l_2 l_3 \sin q_3 + \frac{1}{3}m_3 l_3^2 \sin q_3 \cos q_3)$,
$C_{23} = -\frac{1}{2}\dot{q}_3 m_3 l_2 l_3 \sin q_3$,
$C_{31} = \dot{q}_1(\frac{1}{2}m_3 l_2 l_3 \sin q_3 + \frac{1}{3}m_3 l_3^2 \sin q_3 \cos q_3)$,

- D – vector of gravity

$$D(q) = \begin{pmatrix} 0 \\ (m_2 + m_3)g \\ \frac{1}{2}g m_3 l_3 \cos q_3 \end{pmatrix}. \qquad (23)$$

The effector's position in Cartesian coordinates is

$$p = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos q_1(l_3 \cos q_3 + l_2) \\ \sin q_1(l_3 \cos q_3 + l_2) \\ l_3 \sin q_3 + q_2 \end{pmatrix},$$

and Jacobi matrix is defined as follows

$$J(q) = \begin{bmatrix} J_{11} & 0 & J_{13} \\ J_{21} & 0 & J_{23} \\ 0 & 1 & J_{33} \end{bmatrix}, \qquad (24)$$

$J_{11} = -\sin q_1(l_3 \cos q_3 + l_2)$,
$J_{13} = -\cos q_1 \sin q_3 l_3$,
$J_{21} = \cos q_1(l_3 \cos q_3 + l_2)$,
$J_{23} = -\sin q_1 \sin q_3 l_3$,
$J_{33} = \cos q_3 l_3$.

6.1. Desired Trajectory

For manipulator desired trajectory has been defined as below

$$p_d(t) = \begin{pmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{pmatrix} = \begin{pmatrix} 0.4\cos t \\ 0.4\sin t \\ \frac{t}{10} + 10 \end{pmatrix}, \qquad (25)$$

being a helical line located on the surface of a completely rigid obstacle. The holonomic constraint is therefore defined in the following form

$$\Phi(p) = x^2 + y^2 - 0.4^2 = 0. \qquad (26)$$

Desired trajectory (25) has to be located on obstacle surface, which is given in Cartesian coordinates. For this reason it is necessary to transform it to joint space. Using Newton algorithm [19], trajectory can be represented as solution of following equation (for initial condition $k(q_d(0)) - p_d(0) = 0$) :

$$\dot{q}_d = J^{-1}(q_d)[\dot{p}_d - \gamma(k(q_d) - p_d)], \qquad (27)$$

where:
- q_d, $\dot{q}_d$ – desired position and velocity in joint space,
- p_d, $\dot{p}_d$ – desired position and velocity in Cartesian space,
- $\gamma > 0$ – convergence coefficient; assumed $\gamma = 7$,
- $k(q_d)$ – end-effector position expressed as a function of q_d.

6.2. Force Simulation

To control contact between manipulator and surface it is necessary to get information about contact force. Contact force can be measured (if there is an actual manipulator equipped with appropriate sensors [21]) or calculated based on Lagrange multipliers and definition of holonomic constraint [13].

The Lagrange multipliers λ can be calculated by double differentiation, in time domain, the holonomic constraints equation (1)

$$\ddot{\phi}(q) = \dot{J}\dot{q} + J\ddot{q} = 0. \qquad (28)$$

After substituting $\ddot{q}$ from dynamics equation of the manipulator (2), the equation (28) takes form

$$\ddot{\phi}(q) = J_\xi M^{-1} J^T \lambda + \dot{J}\dot{q} - JM^{-1}(C\dot{q} + D - u) = W(\phi).$$

Equation (28) does not guarantee that $\phi(q) = 0$ will be always fulfilled. To assure it, even if manipulator is in some distance from surface of holonomic constraint, a numerical damping terms [13] are added to the system in the form of the following equation

$$W(\phi) = \ddot{\phi}(q) + 2\alpha\dot{\phi}(q) + \beta^2\phi(q),$$

where α and β coefficients should guarantee asymptotic stability.

After the above steps, the holonomic Lagrange multipliers fulfil

$$JM^{-1}J^T\lambda = W(\phi) - \dot{J}\dot{q} + JM^{-1}(C\dot{q} + D - u).$$

6.3. Results for the Manipulator on the Constraint

According to the assumption, that holonomic constraint fulfils $\Phi = 0$, the initial conditions were chosen as $x(0) = 0.4$, $y(0) = 0$, $z(0) = 7$, to guarantee that manipulator end-effector is in contact with the surface. While desired force was chosen as $f_d = 10$N.

In fig. 2(a) tracking of the desired trajectory in 3D-space by the manipulator has been presented. Since the end-effector is supposed to be on the obstacle, the real trajectory coincides with the set in coordinates x and y. Whereas initial condition $z(0)$ was chosen to show that the manipulator's end-effector approaches the desired trajectory. Figures 2(c)–2(e) show position errors (in Cartesian space) in time domain as follows $e_x = x - x_d$, $e_y = y - y_d$ and $e_z = z - z_d$. While on the fig. 2(b) there is a force error in time domain $e_f = f - f_d$.

6.4. Results for the Manipulator off the Constraint

In section 6.3 results for the manipulator which were constantly on constraint were presented. However, as it was mentioned in the introduction, many tasks require three phase of control, and only last one is exerting a given force (being in contact with an obstacle). For this reason two-stage control is unavoidable, and both, position and position-force control are required. The first stage is position control to approach the end-effector to an obstacle. The second, when the manipulator is on the constraint, position-force control (exerting force on an obstacle) is required.

For the first part – position control in the free space, nominal reference signal was given as

$$\dot{q}_r = \dot{q}_d - \Lambda e_q, \tag{29}$$

and control law was

$$u = M(q)\ddot{q}_r + C(q,\dot{q})\dot{q}_r + D(q) - K_d s, \tag{30}$$

where s is sliding variable defined as $s = \dot{q} - \dot{q}_r = \dot{e}_q + \Lambda e_q$.

When the manipulator was on constraint (end-effector was in contact with an obstacle) the control was switched to the form presented in section 6.3. It is important to notice, that in case of no contact with obstacles, in dynamic model (2) part $J^T_{\phi n} f$ is equal 0 (there is no contact force).

The manipulator is a dynamic system. Therefore rapid switching between algorithms may destabilize the system. Moreover, it is not possible to avoid collision. For this reason, in algorithms simulation, the following solutions were utilized

- position control is used for approaching to the obstacle, as long as distance between the end-effector and surface is greater than max_{dist},
- when manipulator is close to constraint surface (distance between the end-effector and the surface is smaller than max_{dist}), then the control takes the form (11). However, because there is no contact with the obstacle, the force is not included in the manipulator dynamics. Moreover, desired force is not constant over time, but depends on actual value

$$f_d = max(P \cdot f, 0), \tag{31}$$

where $P \in (0, 1)$ is a proportionality factor. This solution allows gradual reduction of the actual force, so that when reaching the obstacle the force value is 0 (the manipulator slows down to avoid sudden collision with the environment).

- at the moment of contact with the obstacle, the occurring force will be taken into account in the dynamics equation of the manipulator, desired force is adjusted to the expected constant value f_d.

According to the assumption, that end-effector is off constraint, the initial conditions were chosen as $x(0) = 0.1$, $y(0) = 0.1$, $z(0) = 2$. The results of tracking trajectory are presented in fig. 3(a),(b) (3D and 2D). Figures 3(c)–3(e) present position tracking errors.

Distance max_{dist} was chosen as 0.05, while the manipulator's effector is on a constraint if its distance from the constraints is less than or equal to 0.00001. In order to define the desired force, formula (31) is used while proportionally coefficient $P = 0.5$.

Fig. 4(a) shows the value of the desired force over time, which is 0, when the manipulator is far from the obstacle, and then the force changes accordingly (proportionally to current force value) and finally when the manipulator is close to the surface falls to 0. At the moment when the manipulator is in contact with the obstacle, the value of desired force is set to the expected value $f_d = 10$. The switching moments of the algorithm are shown in fig. 4(a) and fig. 4(c). The first vertical line indicates the time in which the manipulator is close to the obstacle (at a distance less than or equal to max_{dist} from the obstacle). The second vertical line indicates the moment when the manipulator comes into contact with the obstacle. Then the control algorithm is executed in the same way as for the situation described in sec. 6.3. This solution was adopted for computational reasons.

7. Conclusion

As mentioned in the introduction, one of the main strategies for position-force control is hybrid control based on decoupling position and force control. Consequently, the selection of directions of free motion (position control) and other directions, where there is a possibility to exert forces on a contact surface, is required. The choice of the control algorithm is determined by an obstacle shape. In this paper we assume that manipulator has to track trajectory given as a helical line located on the surface of a completely rigid round obstacle. For this kind of tasks it is necessary to choose directions of control in the joint space. Therefore we applied principle of orthogonalisation to provide decoupling of control in joint space. Based on the principle of orthogonalisation presented by Arimoto [1], we proposed modified position-control algorithm. Convergence of its tracking and force errors is proved.

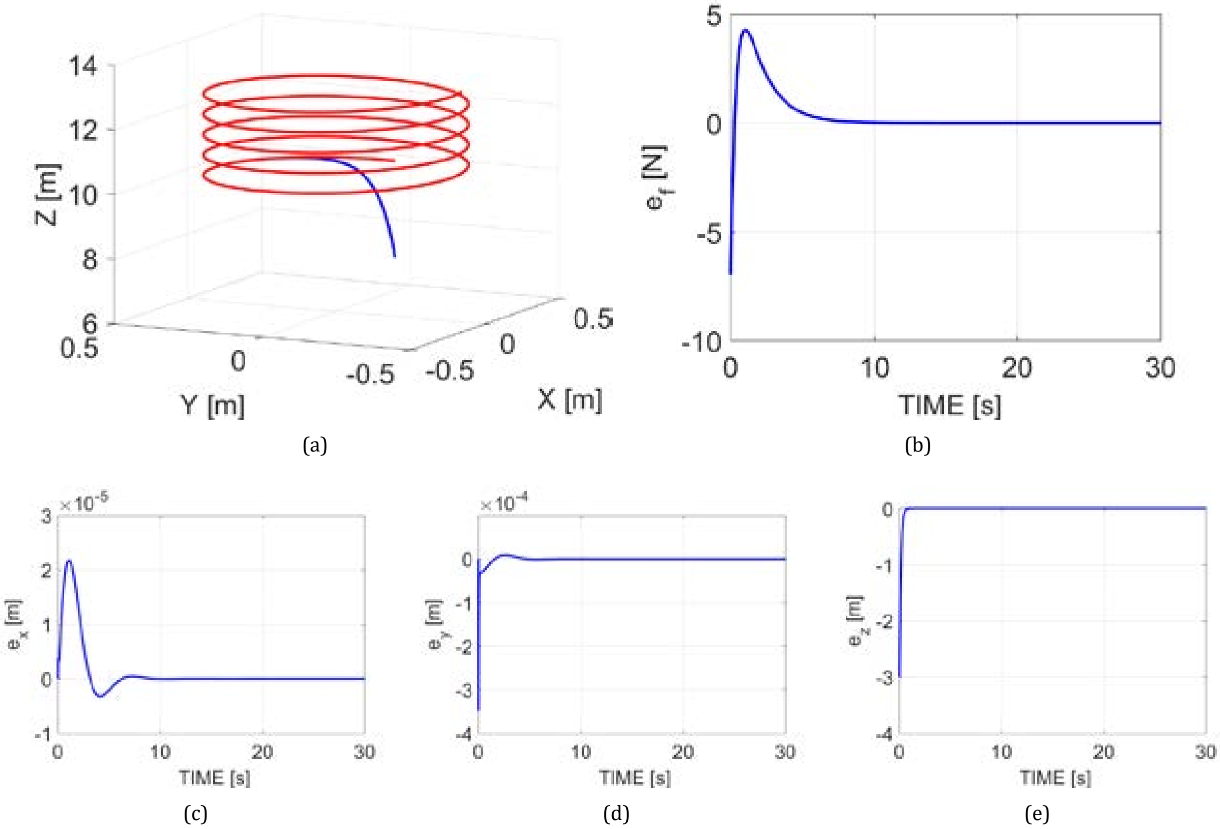

Fig. 2. Modified Arimoto algorithm: (a) trajectory tracking, (b) force tracking error e_f, (c) position tracking error e_x, (d) position tracking error e_y, (e) position tracking error e_z

Correctness of the algorithm is supported by the results of simulations. Simulation test requires information about actual forces. Hence, we used the approach proposed by Mills and Goldenberg [13] providing force simulation in end-effector on the basis of the Lagrange multipliers. The drawback of this method is underlying assumption of total stiffness of the manipulator and obstacles.

The presented position-force control algorithm works correctly and can be used for geometrically constrained fully-known manipulator with rigid obstacles during trajectory tracking. It is dedicated to the situation, when manipulator is in constant contact with the obstacle. In the other situation it is necessary to switch between position control and presented algorithm, according to the movement phase. Assumption of full knowledge about the dynamics is not required. For the parametric uncertainty, when certain number of model parameters is unknown, presented approach can be easily transformed to adaptive case by using classical adaptive algorithm in position part. However, assumption of fully-known rigid obstacles is still necessary.

Future work focuses on the extension of the algorithm to the path following tasks for manipulators and on more detailed considerations about collisions.

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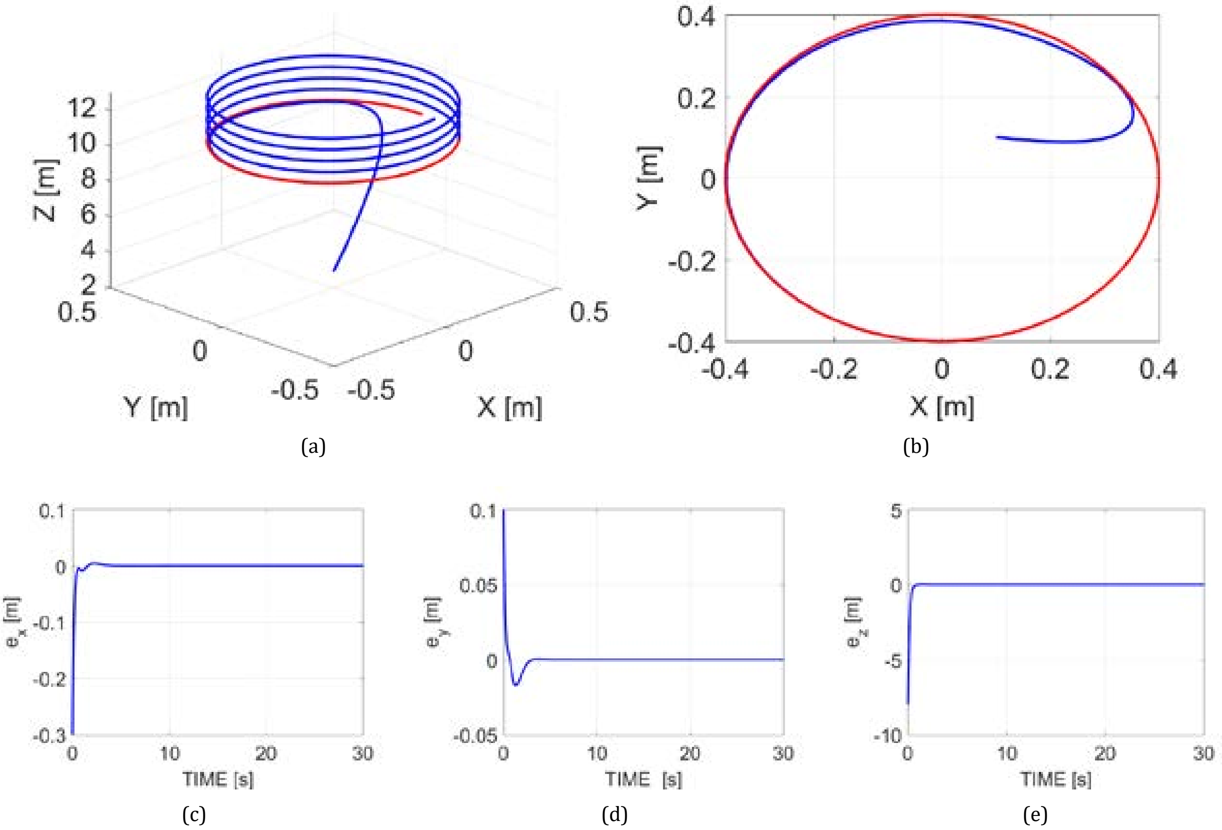

Fig. 3. Modified Arimoto algorithm with approaching phase: (a) trajectory tracking, (b) trajectory tracking - projection on XY plane, (c) position tracking error e_x, (d) position tracking error e_y, (e) position tracking error e_z

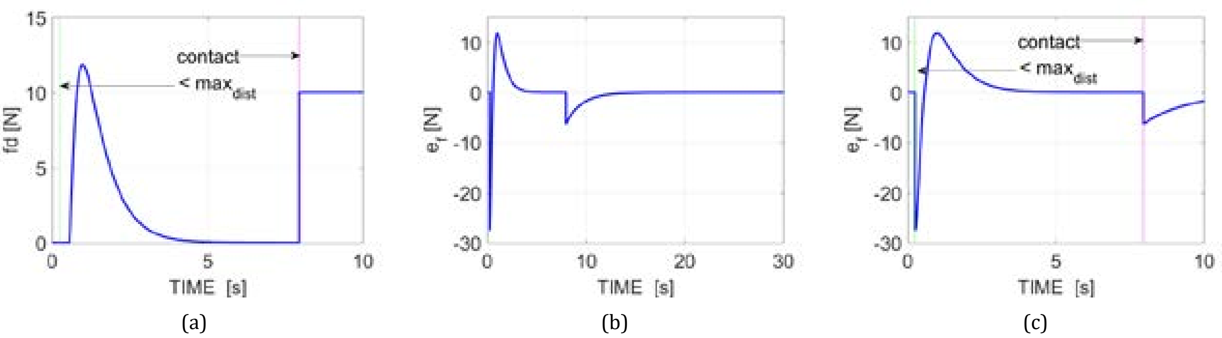

Fig. 4. Modified Arimoto algorithm with approaching phase: (a) desired force in the first 10s of the motion, (b) force tracking error e_f, (c) force tracking error e_f in the first 10s of the motion

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