# Passivity based on Energy Tank for Cartesian Impedance Control of Redundant Free-Flying Space Robots with Elastic Joints

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## Abstract
This paper presents a Cartesian impedance control for free-flying space robots with elastic joints. In order to archive high dynamic behavior of the end-effector like a mass-spring-damper system, the control stiffness and control damping are computed online depending on the Cartesian robot mass matrix and thus time-varying. Therefore, in order to ensure passivity of the system the control law is extended using the concept of energy tank so that the system can achieve maximal performance and simultaneously shows stable behavior both in free motion and in contact with its environment. The proposed control method is very efficient and practicable. Furthermore, it is very robust with respect to dynamic parameter uncertainties, coupling dynamics, and can simultaneously provide good results in term of the dynamic behavior and position accuracy. Simulation results validate practical efficiency of the controller.

## Keywords
Cartesian impedance control, passivity based-control, flexible joint robots, free-flying robots, space robots.

## 1. Introduction

In recent years the use of robots in space has become more and more of interest. With increasing capability of sophisticated autonomy, the robot can be used in such applications as

- Exploration of distant planets
- Orbital servicing/repair in low earth orbit or geostationary earth orbit
- De-orbiting of failed satellites
- Constructions of heavy structures (e.g. Space Station, Planetary Bases)…

In this paper the control issues of a space robotic arm for orbital servicing missions are considered. Since lightweight and a high load/weight ratio are essential for space robotics, the design of the robot can be optimized by using Harmonic-Drive gear with high gear ratio to reduce robot weight [1], [2]. But, high gear ratio causes high motor friction and high joint elasticity, which on the other hand are challenging problems for the robot control. So, for control design the robot is modeled as a redundant free-flying base robot with flexible joints.

In the designed missions the space robot is expected to achieve various tasks, such as capturing a target, constructing a large structure and autonomously maintaining on-orbit systems.

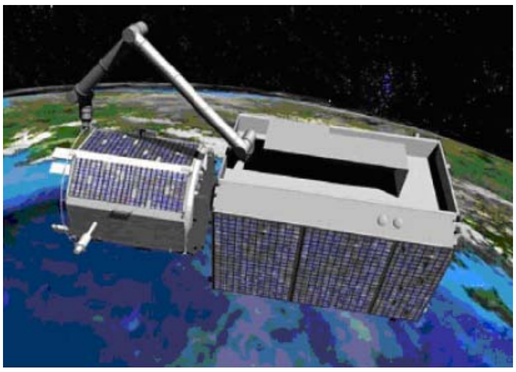

**Fig. 1**: *Target scenario of the space robot.*

In order to allow safe dynamic interaction between the robot and its working environment, a Cartesian impedance controller is needed to reach an interactive behavior with a mass-spring-damper-like disturbance response via active control.

In fixed-base robotic systems, the dynamic interaction between the robot's operational space motions and forces was addressed in the operational Space [3], [4]. The control of free- flying robots for space applications was introduced in [5], [6]. Furthermore, in order to consider uncertainties of the robot parameters or varying parameters, an adaptive control schemes was introduced in [7].

In case of the redundant robot Cartesian impedance control in task space has to take null-space effects into account [4]. The redundant degree of freedom (DOF) can be used to execute several independent tasks while following a strict hierarchy.

Furthermore, in [8] a Cartesian mass matrix is used for control design instead of desired one. But the system passivity could not be ensured for time-varying control gains. In [9] a Cartesian impedance control was introduced based on the concept of energy tank [10], [11], which can be applied to reproduce time-varying stiffness and therefore ensure stable behavior.

In this paper Cartesian impedance control based on energy tank for free-flying base robots with elastic joints is addressed for space applications. It should fulfil the requirements of space missions and must be robust enough for implementation.

The paper is organized as follows. Section 2 introduces the dynamic robot model. In section 3 the control goal for Cartesian impedance control is defined. Section 4 presents the control design for Cartesian impedance controller based on energy tank. The stability of the controlled system is analyzed. Finally, the obtained performance is verified by simulations reported in section 5.

## 2. Modeling Robot Dynamics

Let us consider a redundant space robot with 7 DOF (n=7). The design with 7 joints has some advantages:

- Increased working area
- Increased obstacle avoidance capabilities
- Some redundancy in case of a joint failure.

For control design, the robot is modeled as a flexible joint robot with free-flying base. This robot is equipped with motor position sensors and link torque sensors, which can be used for control. The simplified dynamics of this space robot can be described by

$$u = B\ddot{\theta} + \tau + \tau_f \tag{1}$$

$$\begin{bmatrix} -F_b \\ \tau \end{bmatrix} + \begin{bmatrix} J_b^T \\ J^T \end{bmatrix} F_{ext} = M_s(x_b, q)\begin{bmatrix} \ddot{x}_b \\ \ddot{q} \end{bmatrix} + C_s(x_b, q, \dot{x}_b, \dot{q})\begin{bmatrix} \dot{x}_b \\ \dot{q} \end{bmatrix} \tag{2}$$

$$\tau = K(\theta - q) \tag{3}$$

Therein, $x_b \in R^6$, $q \in R^n$ and $\theta \in R^n$ are the base, link and motor positions, respectively. $u \in R^n$, $\tau_f \in R^n$ present the motor torque and the friction torque. The transmission torque between motor and link dynamics $\tau \in R^n$ is modeled as a linear function of the motor and the link position with the diagonal and positive definite joint stiffness matrix $K \in R^{nxn}$ and can be measured by strain gauge based torque sensors. $F_b, F_{ext} \in R^6$ represent the extern force torque acting on the base and the end-effector (TCP), respectively. $J_b(x_b, q) \in R^{6x6}$, $J(x_b, q) \in R^{6xn}$ are the Jacobian matrices related to the base, and to the arm.

Furthermore, the motor inertia matrix $B \in R^{nxn}$ is diagonal and positive definite. $M_s(x_b, q) \in R^{nxn}$, $C_s(x_b, q, \dot{x}_b, \dot{q}) \in R^{nxn}$ are the mass and the centrifugal/Coriolis matrix, respectively, and $M_s$ can be rewritten as

$$M_s(x_b, q) = \begin{bmatrix} M_b & M_c \\ M_c^T & M \end{bmatrix} \text{ with } \begin{cases} M_b \in R^{6x6} \\ M_c \in R^{6xn} \\ M \in R^{nxn} \end{cases}. \tag{4}$$

Finally, in order to facilitate the controller design and the stability analysis, the following four properties are used

**P.1:** The mass matrix $M_s(x_b, q)$ is symmetric and positive definite (p.d.) and

$$M_s(x_b, q) = M_s^T(x_b, q) > 0$$

**P.2:** The Cartesian mass matrix $\Lambda(x_b, q)$ is p.d. and symmetric

$$I\lambda_{\min} \le \Lambda(x_b, q) \le I\lambda_{\max}$$

with $\lambda_{\min}, \lambda_{\max}$ being maximal and minimal eigenvalue of $\Lambda(x_b, q)$.

**P.3:** For space robots the maximal joint velocity is limited) and it yields

$$-I\gamma_{\max} \le \dot{\Lambda} \le I\gamma_{\max} \text{ with } \gamma_{\max} > 0.$$

**P.4:** In the following it is assumed that total linear and angular momentum is zero

$$H = M_b\dot{x}_b + M_c\dot{q}$$

Which describes the resulting disturbance motion of the base when there is joint motion $\dot{q}$ in the manipulator arm, can be neglected. It is noted that this motion can be actively compensated by satellite.

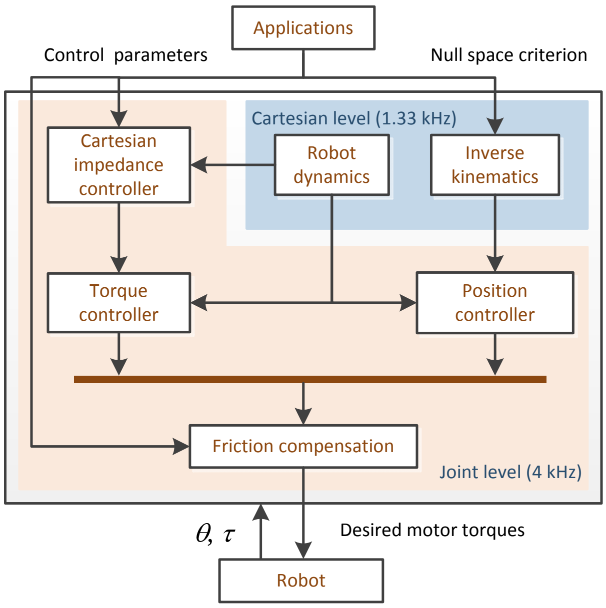


**Fig. 2**: *Robot control structure.*

## 3. Control Goal

In the following it is assumed that the position and orientation of the manipulator's end-effector is defined by $x = f(q, x_b) \in R^6$, where $f(q, x_b)$ represents the forward kinematics of the manipulator and is known. Then, let us define the Cartesian position errors as

$$e_x = x - x_d \tag{5}$$

The goal of the impedance Cartesian control is to achieve the dynamic behavior of the end-effector like a mass-spring-damper system in present of the external force and torque $F_{ext}$

$$\Lambda(x_b, q)\ddot{e}_x + D_c(x_b, q)\dot{e}_x + K_c(x_b, q)e_x = F_{ext} \tag{6}$$

with $\Lambda(x_b, q), D_c(x_b, q), K_c(x_b, q) \in R^{6x6}$ being the Cartesian mass matrix of the robot, the control damping matrix and the control stiffness matrix, respectively.

In order to achieve good dynamic behavior the control damping matrix $D_c$ and the control stiffness matrix $K_c$ in (6) are computed online depending on the Cartesian mass matrix $\Lambda(x_b, q)$.

So, for a given positive definite, symmetric matrix $\Lambda(x_b,q)$, matrices $P(x_b,q), Q(x_b,q) \in R^{6x6}$ can be found so that $\Lambda = PQ$. By choosing matrices

$$\begin{cases} D_c(x_b,q) = 2P(x_b,q)D_\xi K_\omega Q(x_b,q) \\ K_c(x_b,q) = P(x_b,q)K_\omega^2 Q(x_b,q) \end{cases} \quad (7)$$

with positive definite and diagonal constant matrices $D_\xi$ ($D_\xi = diag(\xi_i)$ with $0 < \xi_i \le 1$) and $K_\omega$, the matrices $D_c(x_b,q)$ and $K_c(x_b,q)$ are positive definite as well. If $\xi_i = 1$ the closed-loop system has six real poles, otherwise six complex poles. Obviously, (P.2) leads to

$$\begin{cases} D_{c_{\min}} \le D_c(x_b,q) \le D_{c_{\max}} \\ K_{c_{\min}} \le K_c(x_b,q) \le K_{c_{\max}} \end{cases}. \quad (8)$$

Now, the system can be decoupled by choosing a new coordinate $e_{xq} = Qe_x$. It leads to six decoupled mass-spring-damper subsystems with the desired damping and stiffness behavior

$$\ddot{e}_{xq} + 2D_\zeta K_\omega \dot{e}_{xq} + K_\omega^2 e_{xq}. \quad (9)$$

It is noticed that in this control law the control gain $K_c(x_b,q)$ and $D_c(x_b,q)$ vary with time.

# 4. Proposed Cartesian Impedance Control

In order to eliminate the friction effects and reduce the motor inertia, the Cartesian impedance control is designed by using a cascaded structure [7] consisting of a torque controller as inner control loop and a Cartesian impedance controller as outer control loop in Fig. 2. In this control structure the Cartesian impedance controller computes the desired link torque for the torque controller.

## 4.1. Torque Controller

Let us define the desired link torque as $\tau_d$. Then, for a given desired torque vector $\tau_d$, a torque controller [10], [11]

$$u = K_T(\tau_d - \tau) - K_S\dot{\tau} + \tau_d + \tau_f \quad (10)$$

with p. d. and diagonal control matrices $K_T, K_S$ can stabilize the torque dynamics around the equilibrium point $\tau = \tau_d$ The friction effects $\tau_f$ are preferably compensated by using observer-based friction compensation [14].

The singular perturbation theory leads to the following link dynamics, with the assumption of no external forces\toques on the base ($F_b = 0$)

$$\begin{bmatrix} 0 \\ \tau_d \end{bmatrix} + \begin{bmatrix} J_b^T \\ J^T \end{bmatrix} F_{ext} = M_{gs}(x_b,q)\begin{bmatrix} \ddot{x}_b \\ \ddot{q} \end{bmatrix} + C_s(x_b,q,\dot{x}_b,\dot{q})\begin{bmatrix} \dot{x}_b \\ \dot{q} \end{bmatrix} \quad (11)$$

with

$$M_{gs}(x_b,q) = \begin{bmatrix} M_b & M_c \\ M_c^T & (M + (I+K_T)^{-1}B) \end{bmatrix}. \quad (12)$$

In case of the redundant manipulator, it is well known that some motions of the joints are embedded in the null space of the manipulator's Jacobian matrix J($q$), which do not affect the end-effector position and orientation. Therefore, the desired torque is proposed as

$$\tau_d = J^T F_c + N\tau_n \quad (13)$$

with $F_c \in R^n$ being the desired Cartesian impedance force. $\tau_n \in R^n$ is an arbitrary generalized joint torque of the manipulator, which is projected to the null space of $J^T$ through the projection matrix $N(x_b,q) \in R^{nxn}$.

In this paper we assume that the null space behavior is characterized in joint space by a desired positive definite stiffness $K_n$ and a desired positive definite damping $D_n$ as well as an equilibrium position $q_n$. So, the desired nullspace torque can be computed by a joint level PD controller and chosen as

$$\tau_n = K_n(q_n - q) - D_n\dot{q}_n. \quad (14)$$

In the following the desired Cartesian impedance torque $F_c$ can be computed to realize the closed-loop dynamics (6).

## 4.2. Cartesian Impedance Control Design

Let us define

$$J_s(x_b,q) = \begin{bmatrix} I & 0 \\ 0 & J(x_b,q) \end{bmatrix}, \quad N_s(x_b,q) = \begin{bmatrix} 0 \\ N(x_b,q) \end{bmatrix}. \quad (15)$$

Hereby, I and 0 denote the appropriate identity matrix and zero matrix.

By inserting (13), (15) into (11) the robot dynamics (11) can be rewritten as

$$J_s^T \begin{bmatrix} J_b^T F_{ext} \\ F_c + F_{ext} \end{bmatrix} + N_s\tau_n = M_{gs}\begin{bmatrix} \ddot{x}_b \\ \ddot{q} \end{bmatrix} + C_s\begin{bmatrix} \dot{x}_b \\ \dot{q} \end{bmatrix} \quad (16)$$

From the definition of the generalized Jacobian $J_s$ in (15), the general velocity vector in Cartesian coordinates $J_s = \begin{bmatrix} x_b & x \end{bmatrix}^T$ can be written as

$$\begin{bmatrix} \dot{x}_b \\ \dot{x} \end{bmatrix} = J_s\begin{bmatrix} \dot{x}_b \\ \dot{q} \end{bmatrix} \quad (17)$$

which yields the relevant mapping between general joint and general Cartesian acceleration of the complete system's dynamics

$$\begin{bmatrix} \ddot{x}_b \\ \ddot{x} \end{bmatrix} = J_s\begin{bmatrix} \ddot{x}_b \\ \ddot{q} \end{bmatrix} + \dot{J}_s\begin{bmatrix} \dot{x}_b \\ \dot{q} \end{bmatrix} \quad (18)$$

By pre-multiplying (16) with $(J_s M_{gs}^{-1})$ and using (18) one can obtain the relationship between the general Cartesian acceleration and the Cartesian commanded force $F_c$

$$\begin{bmatrix} J_b^T F_{ext} \\ F_c + F_{ext} \end{bmatrix} + J_s M_{gs}^{-1} N_s \tau_n = \Lambda_s \begin{bmatrix} \ddot{x}_b \\ \ddot{x} \end{bmatrix} + \phi_s \quad (19)$$

with

$$\begin{cases} \Lambda_s(x_b,q) = (J_s M_{gs}^{-1} J_s^T)^{-1} \equiv \begin{bmatrix} \Lambda_b & \Lambda_c \\ \Lambda_c^T & \Lambda \end{bmatrix} \\ \phi_s(x_b,q,\dot{x}_b,\dot{q}) = (J_s M_{gs}^{-1} C_s - \dot{J}_s)\begin{bmatrix} \dot{x}_b \\ \dot{q} \end{bmatrix} \equiv \begin{bmatrix} \phi_{s1} \\ \phi_{s2} \end{bmatrix} \end{cases}. \quad (20)$$

By using definitions (12) and (15) it follows

$$J_s M_{gs}^{-1} N_s \tau_n = \begin{bmatrix} -M_b^{-1} M_c M_\sigma^{-1} N \\ J M_\sigma^{-1} N \end{bmatrix} \tau_n \qquad (21)$$

with

$$M_\sigma = (M + (I + K_T)^{-1} B) - M_c^T M_b^{-1} M_c \,. \qquad (22)$$

For the dynamic consistency of the null space, the projection matrix N should be chosen so that $J M_\sigma^{-1} N = 0$. In [4] this was proposed by

$$N(x_b, q) = (I - J^T \Lambda_\sigma J M_\sigma^{-1}) \qquad (23)$$

with $\Lambda_\sigma$ being an equivalent Cartesian mass matrix of the manipulator and defined by

$$\Lambda_\sigma = (J M_\sigma^{-1} J^T)^{-1} \,. \qquad (24)$$

It is noticed that outside of the singular configuration of the manipulator the matrix $\Lambda_\sigma$ and the respective matrix $\Lambda_s$ are full rank and invertible.

For the chosen $N(x_b, q)$ in (23), the general Cartesian dynamics (19) is reduced into

$$\begin{bmatrix} J_b^T F_{ext} \\ F_c + F_{ext} \end{bmatrix} - \begin{bmatrix} M_b^{-1} M_c M_\sigma^{-1} N \tau_n \\ 0 \end{bmatrix} = \begin{bmatrix} \Lambda_b & \Lambda_c \\ \Lambda_c^T & \Lambda \end{bmatrix} \begin{bmatrix} \ddot{x}_b \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} \phi_{s1} \\ \phi_{s2} \end{bmatrix} \qquad (25)$$

By canceling out the base acceleration $\ddot{x}_b$ in (25) one becomes the equation of robot motion in Cartesian space

$$\begin{aligned} F_c + \Psi F_{ext} &= \Lambda_\sigma \ddot{x} - \Lambda_c^T \Lambda_b^{-1} M_b^{-1} M_c M_\sigma^{-1} N \tau_n \\ &\quad - \Lambda_c^T \Lambda_b^{-1} \phi_{s1} + \phi_{s2} \end{aligned} \qquad (26)$$

with

$$\begin{cases} \Lambda_\sigma(x_b, q) = \Lambda - \Lambda_c^T \Lambda_b^{-1} \Lambda_c \\ \Psi(x_b, q) = I - \Lambda_c^T \Lambda_b^{-1} J_b^T \end{cases} .$$

Now, a Cartesian control law is proposed as

$$\begin{aligned} F_c &= \Lambda_\sigma \ddot{x}_d - \Lambda_c^T \Lambda_b^{-1} M_b^{-1} M_c M_\sigma^{-1} N \tau_n \\ &\quad - \Lambda_c^T \Lambda_b^{-1} \phi_{s1} + \phi_{s2} - D_c(x_b, q) \dot{e}_x - K_c(x_b, q) e_x \end{aligned} . \qquad (27)$$

Substituting (27) into (26) yields

$$\Lambda_\sigma(x_b, q) \ddot{e}_x + D_c(x_b, q) \dot{e}_x + K_c(x_b, q) e_x = \Psi F_{ext} \,. \qquad (28)$$

The expression in (28) establishes a relationship through a generalized mechanical impedance between the vector of resulting forces $\Psi F_{ext}$ and the vector of displacements $e_x$. In order to avoid the coupled motion attributed by $\Psi$ it is necessary to measure the forces\torques $F_{ext}$ or to simplify the dynamic equation of the system.

### 4.3. Cartesian Impedance Controller base on Energy Tank

From assumption P.4, the velocity $\dot{x}_b$ in local coordinates of the base robot can be neglected and the constraint for the dynamics is given by

$$\begin{cases} x_b(t) = const \\ \dot{x}_b(t) = \ddot{x}_b(t) = 0. \end{cases} \qquad (29)$$

Hence, from (25) the dynamic equation of the manipulator is given by

$$F_c + F_{ext} = \Lambda(x_b, q) \ddot{x} + \phi_{s2}(x_b, q, 0, \dot{q}) \,. \qquad (30)$$

Now, the Cartesian impedance control law can be developed by using the dynamic equation (30). Because the proposed control gains $K_c$, $D_c$ in Sec. 3 vary with time, a Cartesian impedance control law as [8] cannot ensure passivity of the pair $\{\dot{e}_x, F_{ext}\}$ using the storage function

$$V = \frac{1}{2} \dot{e}_x^T \Lambda(x_b, q) \dot{e}_x + \frac{1}{2} e_x^T K_c(x_b, q) e_x \,. \qquad (31)$$

Therefore, a new control law is proposed based on energy tank which is used to store the energy dissipated by the controlled system. By introducing a state variable $x_t \in R$ ( $x_t(t=0) > 0$ to avoid singularity) with the store function of the tank

$$T = \frac{1}{2} x_t^2 \,, \qquad (32)$$

the closed-loop dynamics (6) is expanded and given by

$$\begin{cases} \Lambda(x_b, q) \ddot{e}_x + D_{\text{var}}(x_b, q, 0, \dot{q}) \dot{e}_x + K_{const} e_x - w x_t = F_{ext} \\ \dot{x}_t = \dfrac{\delta}{x_t} (\dot{e}_x^T D_{\text{var}}(x_b, q, 0, \dot{q}) \dot{e}_x) - w^T \dot{e}_x \end{cases} \qquad (33)$$

with

$$D_{\text{var}}(x_b, q, 0, \dot{q}) = D_C(x_b, q) - \frac{1}{2} \dot{\Lambda}(x_b, q) \,. \qquad (34)$$

In the following it is resumed the desired damping matrix $D_c(x_b, q)$ is chosen big enough and together with the assumption P.3 it yields $D_{\text{var}}(x_b, q, 0, \dot{q}) > 0$.

Furthermore, $K_{c_{const}} \in R^{nxn}$ is the constant control stiffness and from (8) it is chosen to $K_{c_{const}} = K_{c_{\min}}$. $\delta$ (with $0 < \delta \le 1$) is a constant to scale the dissipated energy in the tank and simultaneously to ensure this being not larger than the dissipated energy of the main control. Finally, $w \in R^n$ presents a new control input to control the energy exchange between the main control law and the tank, and is chosen to

$$w = \begin{cases} -\dfrac{(K_c - K_{c_{const}}) e_x}{x_t} & \text{if} \quad T(x_t) \ge \varepsilon \\ 0 & \quad\;\; T(x_t) < \varepsilon \end{cases} . \qquad (35)$$

For the desired dynamics (33) the control input $F_c$ in (30) is proposed by

$$F_c = \Lambda(x_b, q) \ddot{x}_d - D_c(x_b, q) \dot{e}_x - K_{c_{const}} e_x + w x_t + \phi_{s2}(x_b, q, 0, \dot{q}) \qquad (36)$$

If $T(x_t) \geq \varepsilon$ the desired closed-loop dynamics (6) is present, otherwise a new closed-loop dynamics

$$\Lambda(x_b, q)\ddot{e}_x + D_c(x_b, q)\dot{e}_x + K_{c_{const}} e_x = F_{ext} \qquad (37)$$

is created. Now, we consider the store function

$$V_1 = \frac{1}{2}\dot{e}_x^T \Lambda(x_b, q)\dot{e}_x + \frac{1}{2} e_x^T K_{c_{const}} e_x + \frac{1}{2} x_t^2 . \qquad (38)$$

Then the derivative of the function $V_1$, by using equations (33), (35), and (37), leads to

$$\dot{V}_1 = \dot{e}_x^T F_{ext} - \dot{e}_x^T (1-\delta) D_{var} \dot{e}_x \leq \dot{e}_x^T F_{ext} . \qquad (39)$$

Obviously, the controlled system ensures passivity of the pair $\{\dot{e}_x^T F_{ext}\}$.

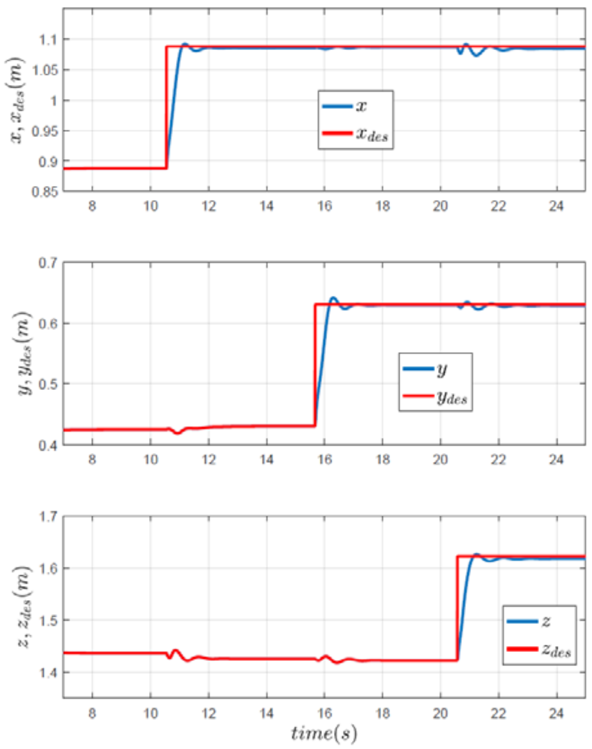


**Fig. 3**: *Step response of the controller*.

## 5. Simulation

The complete control structure of the robot is proposed in Fig. 2 consisting of a joint torque controller, a tracking joint position controller (state feedback controller with position integrator terms) and a Cartesian impedance controller which allows the robot work in two control modes, either with high position accuracy or with safe interaction.

Because of the slow system dynamics and the high required computing time, the robot dynamics and inverse kinematics as well as the control gains of the Cartesian impedance controller are computed online at 1.33 kHz sampling rate, whereas the position controller, the torque controller, the Cartesian impedance controller, as well as the friction compensation are implemented at 4 kHz sampling rate.

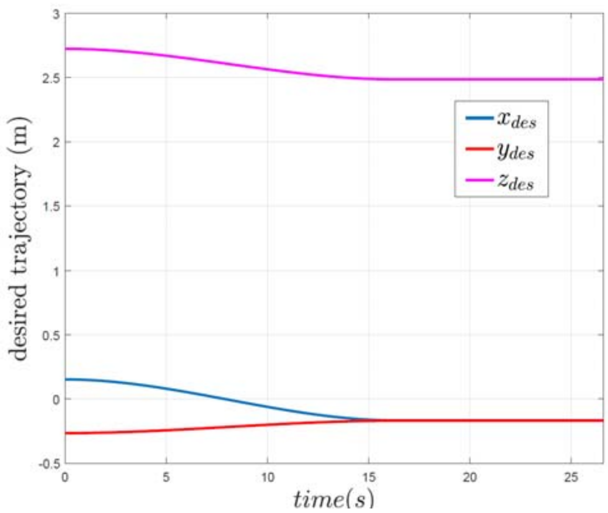


**Fig. 4**: *Desired point-to-point trajectory*.

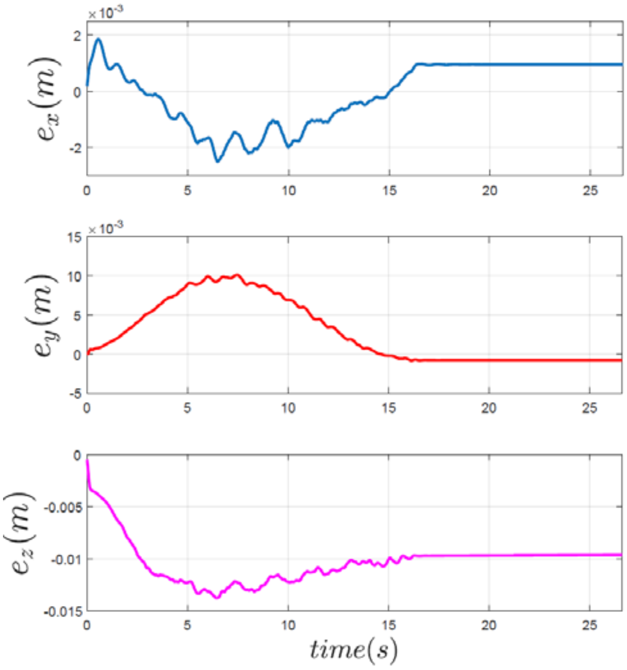


**Fig. 5**: *Cartesian translation position errors*

At first, the control performance in terms of the dynamic behavior of controller is validated by using step response results. It can be seen in Fig. 3 that the proposed controller can damp oscillations of the Cartesian position quite well.

In the next experiment, a point to point trajectory in Fig. 4 is chosen in order to show the position tracking accuracy of the robot. Fig. 5 shows the reached translation position accuracy. It can be seen that the controller can achieve position errors in the order of magnitude of 1cm.

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