Paper

Novel Algorithm for Effective Position/Force Control

Tarik Uzunovic[*a]   Non-member,   Asif Sabanovic[**]   Non-member
Minoru Yokoyama[***]   Student Member,   Tomoyuki Shimono[****]   Senior Member

This paper presents a novel algorithm for simultaneous position and interaction force control. In the classical algorithms, position and force control are executed concurrently by switching between two separate controllers: the position and force controller. Thus, one can consider the control system working in two modes, namely the position control and force control modes. Switching between these two modes often leads to oscillations in the controlled position and force. Therefore, the safe interaction between a controlled mechanical system and its environment is jeopardized. The above issues are tackled in this study by introducing a new control strategy. The proposed algorithm combines position and force control into a single controller, in which the transition between position and force control is smooth, removing the oscillations of classical methods. Therefore, the safe interaction between a mechanical system and its environment is enabled. In addition, using this method one can equip actuators with a control system capable of performing both position and force control. Thus, a step towards "smart actuators" is possible.

Keywords: position/force control, robust control, smart actuators, disturbance observer

1. Introduction

Motion control is the area of research dealing with position and force control of mechanical systems. Thus, there are many effective control algorithms solving position control problems (or trajectory tracking problems), and many of them recently proposed [1]–[4], and also numerous algorithms successfully tackling force control problems, with recent papers [5]–[7]. Depending on a particular application and a desired task, position or force control is necessary [8]. If a mechanical system (for example robot) is required to track a specified trajectory, no matter what kind of interaction it has with its environment, fast and precise position control has to be realized [9]. However, if the interaction with environment is established and the interaction force has to track a specified reference, then force control problem has to be solved [10]. When position and force control are being simultaneously controlled, we are then referring the control problem as position/force control.

With the expansion of robots being active in human

a) Correspondence to: Tarik Uzunovic. E-mail: tuzunovic@etf.unsa.ba
* Faculty of Electrical Engineering, University of Sarajevo
Sarajevo, Bosnia and Herzegovina
** Faculty of Engineering and Natural Sciences, International University of Sarajevo
Sarajevo, Bosnia and Herzegovina and Academy of Sciences and Arts of Bosnia and Herzegovina, Sarajevo, Bosnia and Herzegovina
*** Department of Physics, Electrical and Computer Engineering, Graduate School of Engineering Yokohama National University
Yokohama 240-8501, Japan
**** Faculty of Engineering Division of Intelligent Systems Engineering, Yokohama National University
Yokohama 240-8501, Japan

environment and intensive research in the area of human-robot collaboration, position/force control is a control issue of great importance. The classic methods were actually combining position and force controllers derived as separate algorithms, in such a way that switching between position and force control is present in the control system [11][12]. The switching is often causing oscillations in the controlled quantities, thus making the interaction between robot and its environment dangerous. Since the environment can be human beings, the importance of solution for this problem is rising. Some approaches to synthesize position control and force control without switching are also presented [13]. In this case, since it often needs some weighting factor and/or frequency-based decoupling, the design procedure to merge two controllers tends to be complicated and the compromise between two controllers sometimes leads to the deterioration of total control performance.

The concurrent position and force control on a single-DOF manipulator is not feasible so the solution which had been sought in the hybrid control schemes switching between position and force control is applied on one or another way. The concept is introduced in [14]. In the robotics framework the problem had been addressed in different framework like: artificial constraint task formulation [15], the operational space formulation with inclusion of the manipulator dynamic model [16], the constrained motion formulation [17]. A parallel force/position regulator was developed in [18]. The paper [19] presents a systematic method for modeling the interaction of a robot with a dynamic environment. Another generalization of the approach from [14] is presented in [17], with the major difference that the manipulator dynamics has been taken into account rigorously. Position and contact force control during constrained motion have been investigated in [20], by applying design of controller parameters based on a linearized

dynamic model of the manipulator during constrained motion. Duffy pointed out a problem of invariance in hybrid position/force control which arises from wrong definition of orthogonality applied to instantaneous rigid-body motions and equally to forces/couples in combinations, [21]. This problem of invariance is addressed in [22]. The constrained motion formulation was recently employed in [23], where an adaptive control law is presented. In [24], position/force control is discussed for constrained mobile manipulators. The control scheme combines model-based computed torque controller with model free neural-network-based controller. Hybrid position/force control of robotic manipulators is presented in [25]. The dynamic model of the robotic manipulator performing operations on a surface was decomposed into force, position, and redundant joint subspaces, while the control strategy was adaptive fuzzy sliding mode control.

The impact force limitation and unstable behavior during impact are recognized as problems; thus, many schemes are developed under assumption that the contact with environment is established. Therefore, there is still the need for analysis of control schemes including the transition from non-contact to contact situations and vice versa. In this paper we are discussing a problem of a hybrid position/force control in the unified framework of the acceleration control with an idea that the position and force are controlled by the same controller and the hybridization is achieved at the level of the control error formulation.

This paper is organized as follows. The proposed control strategy is presented in Section II. Its validation in simulations was shown in Section III, while the experimental results are given in Section IV. The last section gives concluding remarks and directions for the future work.

2. Control Strategy Description

If one thinks about applications in which position and force control have to be combined, let us discuss the following application. A robot is controlled to track a reference trajectory in an environment with obstacles. Once the reference trajectory goes "inside" an obstacle, the robot cannot track it any more. The tracking error is rising, control forces imposed to the robot's joints are increasing. Thus, the robot is trying to "push" the obstacle with maximum force. As the result, the robot or the obstacle might be physically damaged. The question is how to prevent such a situation. Obviously, once the robot comes into the physical contact with the obstacle, the control algorithm should switch from the position control mode to the force control mode, and interaction force between the robot and obstacle is to be controlled. Smooth transition between these two modes is of crucial importance. On the other hand, if service robots are considered, obstacles for them may be human beings, and interaction force control, or limitation of the interaction force, is now even more important.

The whole explanation will be given for an actuated mechanical system with single degree of freedom that can be described as [26]

$$a(q)\ddot{q} + b(q,\dot{q}) + g(q) + \tau_{ext} = \tau. \cdots\cdots\cdots\cdots (1)$$

In (1), q is the system position; $a(q)$ stands for the system inertia; $b(q,\dot{q})$ represents Coriolis forces, viscous friction

forces, and centripetal forces; $g(q)$ stands for the gravity force; τ_{ext} is the external force acting on the system; and τ denotes the control force or input force.

It is possible to define the disturbance as $\tau^{dis} = b(q,\dot{q}) + g(q) + \tau_{ext} + \Delta a(q)\ddot{q} = a_n(q)\ddot{q}^{dis}$, and then use a disturbance observer to estimate it. The system inertia is expressed as $a(q) = a_n(q) + \Delta a(q)$, where $a_n(q)$ is the known nominal value, while $\Delta a(q)$ stands for the unknown variation of the inertia. The following control force is exerted to the robot

$$\tau = a_n(q)\ddot{q}^{cmd} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

which makes possible to express (1) in terms of accelerations as

$$\ddot{q} = \ddot{q}^{cmd} - \ddot{q}^{dis}. \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Here, the classical disturbance observer (denoted as DOB_q) can be applied [27]–[29] in order to obtain $\hat{\ddot{q}}^{dis}$ as follows

$$\hat{\ddot{q}}^{dis} = (\ddot{q}^{cmd} + g_q\dot{q})Q_q - g_q\dot{q}, \quad Q_q = \frac{g_q}{s+g_q} \quad \cdots\cdots\cdots (4)$$

where g_q is the cut-off frequency of the first-order low-pass filter Q_q.

Once $\ddot{q}^{dis}$ is estimated as $\hat{\ddot{q}}^{dis}$, $\ddot{q}^{cmd}$ is obtained as $\ddot{q}^{cmd} = \ddot{q}^{des} + \hat{\ddot{q}}^{dis}$, where $\ddot{q}^{des}$ is the desired acceleration, since $\ddot{q} = \ddot{q}^{des}$ enforces desired dynamics of the controlled system. Since the disturbance estimation error always exists, the dynamics becomes

$$\ddot{q} = \ddot{q}^{des} + \left(\hat{\ddot{q}}^{dis} - \ddot{q}^{dis}\right). \cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

If a good disturbance compensation exists, estimation error is sufficiently small. In that case, only desired acceleration $\ddot{q}^{des}$ has to be selected. Therefore, for the sake of easier derivation, it will be assumed that $\ddot{q} = \ddot{q}^{des}$ is valid.

Before we go into the mathematical definition of our method, let us first explain reasoning behind the whole idea. For the sake of simplicity, the whole idea is presented for 1-DOF systems. If a controlled mechanical system (let us call it robot for shorter writing), with position q is in free motion and has to follow a reference trajectory q^{ref}, then the control algorithm has to enforce the robot to stay on the desired trajectory described by $e = q - q^{ref} = 0$, where e is the tracking error. Figure 1 illustrates the basic idea. One can also define the position-based generalized error $\sigma = \dot{e} + ce$ with c being a positive constant. The homework of the control system in trajectory tracking task can be to enforce that $\sigma \xrightarrow{t\to\infty} 0$. Thus, input force τ is produced to push the robot towards the desired trajectory, and its value depends on the generalized error as a function $\tau = \phi(\sigma)$. Now, if during its free motion the robot comes into the physical contact with its environment (obstacle) with position q_e, the interaction force f_e appears with a non-zero value. It happens when the obstacle intersects the desired trajectory. During the contact, one would like to have the interaction force follow its prescribed reference f^{ref}. In other words, it would be desired that input force τ now depends on the f_e and reference interaction force f^{ref}. That implies that the definition of generalized error should include the interaction force and its reference. In that way, the force pushing the robot back and forth during the contact would be dependent on f_e and f^{ref}, making the
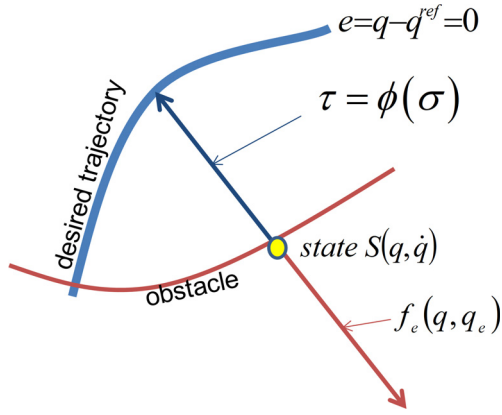
Fig. 1. Representation of the basic idea for control algorithm

force control possible. In this sense, it is similar to the idea of position reference modification once the contact between the robot and its environment is established.

The interaction force could be modeled as follows

$$f_e(q, q_e) = \begin{cases} 0, & \text{no contact} \\ D_e(\dot{q} - \dot{q}_e) + K_e(q - q_e), & \text{in contact} \end{cases}$$
·················· (6)

where D_e and K_e are damping coefficient and stiffness at the interaction point between the robot and environment. Exact values of D_e and K_e are usually not known. One can write $D_e = D_{en} + \Delta D_e$ where D_{en} is the known nominal value and ΔD_e is the unknown variation. In addition, it can be written $K_e = K_{en} + \Delta K_e$, where K_{en} is the known nominal value of the stiffness and ΔK_e is its unknown variation. Now (6), can be rewritten as

$$f_e(q, q_e) = \begin{cases} 0, & \text{no contact} \\ (D_{en} + \Delta D_e)(\dot{q} - \dot{q}_e) + K_e(q - q_e), & \text{in contact} \end{cases}$$
·················· (7)

It is important to note that (7) allows positive and negative interaction force during the contact. It is completely natural. Consider the situation illustrated in Fig. 2 where 1-DOF robot moving along *x*-axis is placed between two obstacles. It can hit an obstacle on both sides, and interaction forces will be of opposite direction in these two cases. Thus, the signs of these two interaction forces are different. Due to this fact, one can define different references for these two forces, let us call them positive reference $f_+^{ref} > 0$ and negative reference $f_-^{ref} < 0$. For example, positive reference can correspond to the interaction force established when the robot is moving in the positive *x*-direction, and negative reference may correspond to the interaction force created when the robot's displacement is in the negative *x*-direction.

Let us now introduce σ_f^* defined as

$$\sigma_f^* = \begin{cases} \sigma, & \text{if } -\rho f_+^{ref} < \sigma < -\rho f_-^{ref} \\ -\rho f_-^{ref}, & \text{if } \sigma \geq -\rho f_-^{ref} \\ -\rho f_+^{ref}, & \text{if } \sigma \leq -\rho f_+^{ref} \end{cases}$$
·········· (8)

where ρ is a positive constant. Thus, σ_f^* is actually saturated position-based generalized error, with upper and down limit dependant on the reference interaction force f^{ref}. Based on σ_f^*, the total generalized error can be described is
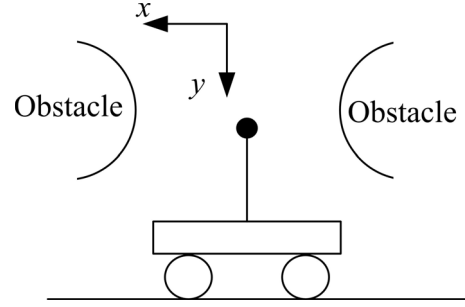

Fig. 2. 1-DOF robot moving between two obstacles

$$\sigma_{f\sigma} = \sigma_f^* + \rho f_e$$ ······························ (9)

If one succeeds to design a control strategy which will enforce the control goal $\sigma_{f\sigma} \xrightarrow{t \to \infty} 0$, it would mean that for $\sigma_{f\sigma} = 0$, it becomes

$$f_e = \begin{cases} -\sigma/\rho, & \text{if } -\rho f_+^{ref} < \sigma < -\rho f_-^{ref} \\ f_-^{ref}, & \text{if } \sigma \geq -\rho f_-^{ref} \\ f_+^{ref}, & \text{if } \sigma \leq -\rho f_+^{ref} \end{cases}$$
······ (10)

From (8)–(10), the following can be concluded. If the robot is in free motion (no contact with the environment), then $f_e = 0$, and $\sigma_{f\sigma} = \sigma_f^*$. Therefore, when the control goal is achieved, $\sigma_f^* = 0 \Rightarrow \sigma = 0 \Rightarrow e = 0$, and desired trajectory is reached. In addition, (10) shows that $f_e = 0$ is compatible with achieved control goal. On the other hand, when the contact is established, desired trajectory cannot be reached, σ_f^* reaches its upper or down limit, and interaction force becomes equal to f_-^{ref} or f_+^{ref}, i.e., its reference. Change in sign is in accordance with already discussed positive and negative sign of the interaction force.

Since it was shown that $\sigma_{f\sigma} \xrightarrow{t \to \infty} 0$ ensures that all control goals are satisfied, it is necessary to discuss how to design $\ddot{q}^{des}$ which enforces that. Taking into account the robot's dynamics $\ddot{q} = \ddot{q}^{des}$, the first-order dynamics for $\sigma_{f\sigma}$ is given by

$$\dot{\sigma}_{f\sigma} = \begin{cases} \ddot{q}^{des} - \ddot{q}^{ref} + c\dot{e} + \rho \dot{f}_e, & \text{if } -\rho f_+^{ref} < \sigma < -\rho f_-^{ref} \\ \rho D_{en}(\ddot{q}^{des} - \ddot{q}_e) + \rho \Delta D_e(\ddot{q}^{des} - \ddot{q}_e) + \rho K_e(\dot{q} - \dot{q}_e) - \rho \dot{f}_-^{ref}, & \text{if } \sigma \geq -\rho f_-^{ref} \\ \rho D_e(\ddot{q}^{des} - \ddot{q}_e) + \rho \Delta D_e(\ddot{q}^{des} - \ddot{q}_e) + \rho K_e(\dot{q} - \dot{q}_e) - \rho \dot{f}_+^{ref}, & \text{if } \sigma \leq -\rho f_+^{ref} \end{cases}$$
·················· (11)

It has to be noted that the first equation in (11) is also valid when no contact exists and $f_e = 0$. In compact form, assuming $\rho = D_{en}^{-1}$, (11) can be written as

$$\dot{\sigma}_{f\sigma} = \ddot{q}^{des} - \sigma_{f\sigma}^{dis}(q, q_e, f_e, \rho)$$ ··················· (12)
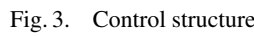
If one assumes that $\sigma_{f\sigma}$ is available, it is possible to estimate $\sigma_{f\sigma}^{dis}(q, q_e, f_e, \rho)$ and obtain $\hat{\sigma}_{f\sigma}^{dis}(q, q_e, f_e, \rho)$ using the classical disturbance observer (denoted as $DOB_{f\sigma}$) as follows

$$\hat{\sigma}_{f\sigma}^{dis}(q, q_e, f_e, \rho) = (\ddot{q}^{des} + g_{f\sigma}\sigma_{f\sigma})Q - g_{f\sigma}\sigma_{f\sigma}, \quad Q_{f\sigma} = \frac{g_{f\sigma}}{s + g_{f\sigma}}$$
······················ (13)

where $g_{f\sigma}$ is the cut-off frequency of the first-order low-pass filter $Q_{f\sigma}$. When $\hat{\sigma}_{f\sigma}^{dis}$ is available, $\ddot{q}^{des}$ can be selected as

$$\ddot{q}^{des} = \hat{\sigma}_{f\sigma}^{dis} + \dot{\sigma}_{f\sigma}^{des}$$ ··························· (14)

where $\dot{\sigma}_{f\sigma}^{des}$ represents desired dynamics of $\dot{\sigma}_{f\sigma}$. The simplest

$$f_e(q,q_e) = \begin{cases} 0 & \text{no contact} \\ f_e & \text{in contact} \end{cases} \quad \sigma_f^* = \begin{cases} \sigma, & \text{if} -\rho f_+^{ref} < \sigma < -\rho f_-^{ref} \\ -\rho f_-^{ref}, & \text{if } \sigma \geq -\rho f_-^{ref} \\ -\rho f_+^{ref}, & \text{if } \sigma \leq -\rho f_+^{ref} \end{cases}$$

$$\sigma = \dot{e} + ce \to 0 \Rightarrow q \to q^{ref}$$

Fig. 3.　Control structure

choice is having

$$\dot{\sigma}_{f\sigma} = -k\sigma_{f\sigma}, \; k > 0. \cdots\cdots\cdots\cdots\cdots\cdots (15)$$

The complete control structure can be represented as in Fig. 3. Here, it is assumed that interaction force is estimated using reaction force observer (DOB_f) [30], as the practical implementations usually omit force sensor. Even though it is very powerful, the proposed algorithm requires only a few control parameters: $c, \rho, g_q, g_{f\sigma}, k$. Thus, its tuning procedure is not very complex.

It is important to say that the same approach can be applied for the interaction force modeled as pure spring. The difference would be that σ_f^* would be saturated tracking error e, and second order dynamics of $\sigma_{f\sigma}$ is being controlled, which would be written in the same form as (12). One would then use control signal $\ddot{q}^{des} = \hat{\sigma}_{f\sigma}^{dis} + \ddot{\sigma}_{f\sigma}^{des}$ with $\ddot{\sigma}_{f\sigma}^{des}$ being desired second order dynamics of $\sigma_{f\sigma}$.

3. Simulation Results

In this section, the proposed control method is tested in simulations. The controlled system was having dynamics described in (1), with parameters and forces modeled as

$$a(q) = 0.1(1 + 0.5\sin(q)) \cdots\cdots\cdots\cdots\cdots (16)$$
$$a_n(q) = 0.1 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (17)$$
$$b(q,\dot{q}) = 5q + 0.02\dot{q} + 0.025\dot{q}\cos(q) \cdots\cdots\cdots (18)$$
$$g(q) = 9.81q^2 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (19)$$
$$\tau_{ext} = \alpha(t)[1(t - 0.2) - 1(t - 0.8)] + f_e \cdots\cdots\cdots (20)$$
$$\alpha(t) = 0.5[1 + \cos(12.56t) + \sin(37.68t)]. \cdots\cdots (21)$$

In (20), 1(t) stands for Heaviside step function. Parameters used in the interaction force model were $K_e = 250\cdot10^3$, $D_e = D_{en} + \Delta D_e = 5$, $D_{en} = 20$, $\Delta D_e = -15$. Interaction force references were

$$f_+^{ref}(t) = -f_-^{ref}(t) = f^{ref}(t) = 10(1 - 0.75\sin(15.28t)).$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots (22)$$

Position reference was

$$q^{ref}(t) = -0.01 + 0.0095\sin(6.28t). \cdots\cdots\cdots\cdots (23)$$

Fig. 4.　Position responses in simulation

Fig. 5.　Force responses in simulation

Position of the environment (obstacle) was taken as

$$q_e(t) = -0.01 + 0.0035\sin(12.56t)[1(t) - 1(t - 1.5)].$$
$$\cdots\cdots\cdots\cdots\cdots\cdots (24)$$
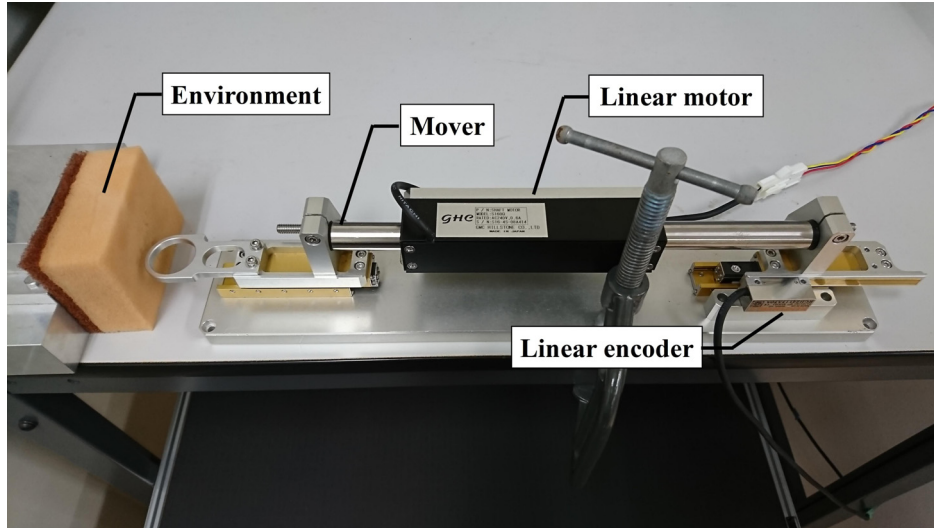
Fig. 6.   Experimental platform

Control parameters were

$$c = 100, \rho = 1/D_{en} = 0.05, g_q = g_{f\sigma} = 1200, k = 35. \qquad (25)$$

In order to have realistic simulation input force τ was limited to ±25.

Simulation results are presented in Figs. 4 and 5. Shaded parts of the graphs correspond to time intervals in which the contact between the controlled system and environment is established. In free motion, the trajectory tracking is successfully realized. This can be observed in the intervals lasting between 0.49 s and 1.01 s, as well as between 1.49 s and 2 s. When the system comes into contact with the environment, and when the reference position cannot be tracked any more, the controller switches to the force control mode. In the force control mode, the reference force is successfully tracked, which can be noticed in the intervals between 0.01 s and 0.49 s, as well as between 1.01 s and 1.49 s. The presented results show that controller is able to work both in the position control mode, as well as in the force control mode. It is important to mention here that exact value of D_e was not assumed to be known, since there was a huge difference between D_{en} and D_e. However, the results still showed very good performance of the control algorithm, which proves the robustness of the presented control method. Thus, the proposed control strategy is not very sensitive against the parameter variation of D_e.

4. Experimental Results

4.1 Experimental Platform   After simulations, an experimental validation of the presented algorithm was done. Experimental platform is depicted in Fig. 6, with major parts marked.

A one degree of freedom linear motor, S160Q from GMC Hillstone Co. Ltd., was used as the controlled system. Nominal mass and thrust constant of the system are 0.6 kg and 33 N/A, respectively. An optical encoder, Renishaw's RGH24Y, whose resolution is 0.1 μm detects the motor position. The motor velocity was calculated by pseudo differential of the position response. The control algorithm

was run by Linux using RTAI, and the sampling time was set to 0.1 ms. A sponge was used as the environment for the force control mode since it was preventing trajectory tracking due to being fixed on one end.

Control parameters were

$$c = 25, \rho = 0.02, g_q = 300, g_{f\sigma} = 200, k = 25. \qquad (26)$$

Lower values of the gains and cut-off frequencies, when compared to simulations, are partly due to lack of velocity measurement, but mostly due to lack of force measurement. The interaction force was estimated using reaction force observer which requires precise model of the friction force, which was in this case hard to obtain. However, that is not the focus of this paper. Thus, better force estimation would enable us to use higher control gains and cut-off frequencies, making the overall control performance better. In addition, simulations always allow higher control gains since all necessary parameters are available. In experiments, the input force was limited to 15 N. The value of D_{en} was not estimated in order to obtain the value of parameter ρ. The value of ρ was selected to be 0.02 which provided satisfactory performance. A control designer may experimentally determine a value of ρ which yields satisfying closed-loop behavior. It has been already shown that control system is pretty robust against variations of D_e.

4.2 Experiment 1   In the first experiment, the reference force was constant $f_+^{ref} = -f_-^{ref} = f^{ref} = 3.5$ N, while the reference position was given as $q^{ref} = 0.003 + 0.019 \sin(2\pi f \cdot t)$ m, $f = 0.2$ Hz. This experiment was created to check whether the proposed method could be used in trajectory tracking tasks, but with present limit on the maximum interaction force imposed to the environment. The recorded results are depicted in Figs. 7 and 8.

The obtained responses show satisfactory performance of the controller. In free motion, reference trajectory is successfully tracked. After the contact with environment is established, the interaction force is controlled not to overcome 3.5 N. It is important to note that smooth transition between position tracking and force control is achieved, and no oscillatory behavior is observed in the controlled quantities,
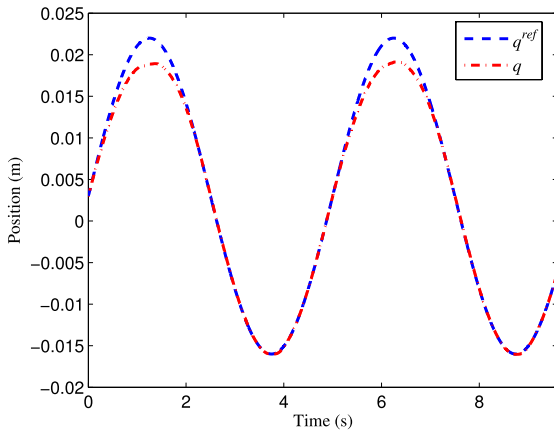
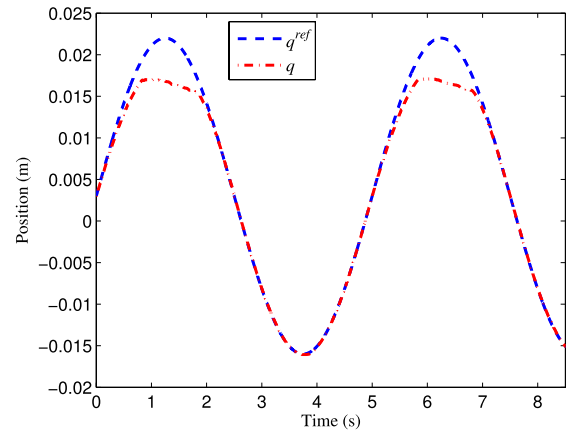Fig. 7.   Position responses in experiment 1
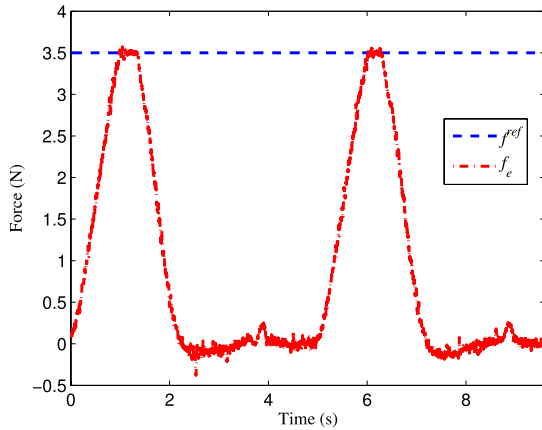

Fig. 9.   Position responses in experiment 2

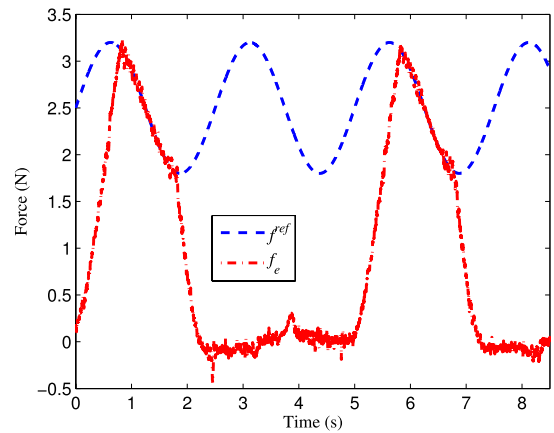Fig. 8.   Force responses in experiment 1

Fig. 10.   Force responses in experiment 2

i.e., there is no so-called "woodpecker phenomenon".

The force response shows some issues that exist with interaction force estimation. The estimation requires precise dynamical model of the controlled system, so that only unknown force is the external interaction force. In this scenario, the interaction force can be estimated using a disturbance observer. However, since some small interaction force is estimated even when no contact exists between the system and environment, this implies that some unmodeled dynamics is still present. Nevertheless, it does not negate the conclusion about the effectiveness of the presented control strategy. Force estimation is not in the focus of this paper. If it was improved, the overall control performance would be improved.

4.3 Experiment 2   In the second experiment, the goal was to have changing force reference, in order to test whether the force tracking is also achievable with the proposed control strategy. Position reference was $q^{ref} = 0.003 + 0.019 \sin(2\pi f \cdot t)$ m, $f = 0.2$ Hz. The reference force was given as $f_+^{ref} = -f_-^{ref} = f^{ref} = 2.5 + 0.7\sin(2\pi f \cdot t)$ N, $f = 0.4$ Hz. The obtained responses are shown in Figs. 9 and 10.

The responses from Figs. 9 and 10 prove that proposed control method is applicable for both position tracking in free motion and force tracking in contact motion. Both of these tasks are successfully executed.

5. Conclusion

In this paper a novel position/force control method is proposed. The method merges the position and force control into a single control structure, capable to enforce the trajectory tracking in free motion, as well as the interaction force control during the contact between a controlled mechanical system and its environment. Satisfactory control performance of this method has been validated through simulations and experiments.

The proposed algorithm is simple and easy to implement, requiring only a few control parameters. Thus, it could be implemented in simple embedded systems which could be added to conventional actuators, making a step towards "smart actuators". With these actuators, one would only need to supply position and force references.

In the future, we plan to explore and experimentally validate the presented control structure for multi-DOF systems, for example robotic manipulators operating in an environment with obstacles.
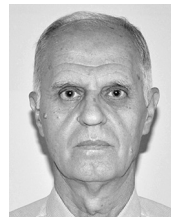
References

(1) G. Zhong, Z. Shao, H. Deng, and J. Ren: "Precise position synchronous control for multi-axis servo systems", *IEEE Trans. Ind. Electron.*, Vol.64, No.5, pp.3707–3717 (2017)

(2) H. Du, X. Chen, G. Wen, X. Yu, and J. Lu: "Discrete-time fast terminal sliding mode control for permanent magnet linear motor", *IEEE Trans. Ind. Electron.* (2018) DOI: 10.1109/TIE.2018.2815942

(3) X. Zhang, T. Shi, Z. Wang, Q. Geng, and C. Xia: "Generalized predictive contour control of biaxial motion system", *IEEE Trans. Ind. Electron.* (2018) DOI: 10.1109/TIE.2018.2808899

(4) W. Zhao, S. Jiao, Q. Chen, D. Xu, and J. Ji: "Sensorless control of linearpermanent-magnet motor based on improved disturbance observer", *IEEE Trans. Ind. Electron.* (2018) DOI: 10.1109/TIE.2018.2823660

(5) K. Zhang, J. Xu, H. Chen, J. Zhao, and K. Chen: "Jamming analysis and force control for flexible dual peg-in-hole assembly", *IEEE Trans. Ind. Electron.* (2018) DOI: 10.1109/TIE.2018.2838069

(6) S. Chen, Z. Chen, B. Yao, X. Zhu, S. Zhu, Q. Wang, and Y. Song: "Adaptive robust cascade force control of 1-dof hydraulic exoskeleton for human performance augmentation", *IEEE/ASME Trans. Mechatronics*, Vol.22, No.2, pp.589–600 (2017)

(7) R. Cortesao and M. Dominici: "Robot force control on a beating heart", *IEEE/ASME Trans. Mechatronics*, Vol.22, No.4, pp.1736–1743 (2017)

(8) A. Šabanović: "Challenges in motion control systems", *IEEJ Journal of Industry Applications*, Vol.6, No.2, pp.107–116 (2017)

(9) T. Oomen: "Advanced motion control for precision mechatronics: Control, identification, and learning of complex systems", *IEEJ Journal of Industry Applications*, Vol.7, No.2, pp.127–140 (2018)

(10) T.T. Phuong, K. Ohishi, C. Mitsantisuk, Y. Yokokura, K. Ohnishi, R. Oboe, and A. Sabanovic: "Disturbance observer and kalman filter based motion control realization", *IEEJ Journal of Industry Applications*, Vol.7, No.1, pp.1–14 (2018)

(11) Q. Xu: "Design and smooth position/force switching control of a miniature gripper for automated microhandling", *IEEE Trans. Ind. Informat.*, Vol.10, No.2, pp.1023–1032 (2014)

(12) G. Wang and Q. Xu: "Design and precision position/force control of a piezo-driven microinjection system", *IEEE/ASME Trans. Mechatronics*, Vol.22, No.4, pp.1744–1754 (2017)

(13) B. Huard, M. Grossard, S. Moreau, and T. Poinot: "Sensorless force/position control of a single-acting actuator applied to compliant object interaction", *IEEE Trans. Ind. Electron.*, Vol.62, No.6, pp.3651–3661 (2015)

(14) M.H. Raibert and J.J. Craig: "Hybrid position/force control of manipulators", *J. Dynamic Syst. Meas. Control*, Vol.103, No.2, pp.126–133 (1981)

(15) M.T. Mason: "Compliance and force control for computer controlled manipulators", *IEEE Trans. Syst., Man, Cybern.*, Vol.11, No.6, pp.418–432 (1981)

(16) O. Khatib: "A unified approach for motion and force control of robot manipulators: The operational space formulation", *IEEE Journal of Robotics and Automation*, Vol.3, No.1, pp.43–53 (1987)

(17) T. Yoshikawa: "Dynamic hybrid position/force control of robot manipulators–description of hand constraints and calculation of joint driving force", *IEEE J. Robot. Autom.*, Vol.3, No.5, pp.386–392 (1987)

(18) S. Chiaverini, B. Siciliano, and L. Villani: "Force/position regulation of compliant robot manipulators", *IEEE Trans. Autom. Control*, Vol.39, No.3, pp.647–652 (1994)

(19) A. De Luca and C. Manes: "Modeling of robots in contact with a dynamic environment", *IEEE Trans. Robot. Autom.*, Vol.10, No.4, pp.542–548 (1994)

(20) J. K. Mills and A.A. Goldenberg: "Force and position control of manipulators during constrained motion tasks", *IEEE Trans. Robot. Autom.*, Vol.5, No.1, pp.30–46 (1989)

(21) J. Duffy: "The fallacy of modern hybrid control theory that is based on "orthogonal complements" of twist and wrench spaces", *Journal of Robotic Systems*, Vol.7, No.2, pp.139–144 (1990)

(22) J. De Schutter, D. Torfs, H. Bruyninckx, and S. Dutré: "Invariant hybrid force/position control of a velocity controlled robot with compliant end effector using modal decoupling", *The International Journal of Robotics Research*, Vol.16, No.3, pp.340–356 (1997)

(23) P. Gierlak and M. Szuster: "Adaptive position/force control for robot manipulator in contact with a flexible environment", *Robotics and Autonomous Systems*, Vol.95, pp.80–101 (2017)

(24) M. Rani, N. Kumar, and H.P. Singh: "Efficient position/force control of constrained mobile manipulators", *International Journal of Dynamics and Control*, pp.1–10 (2018)

(25) A.K. Ravandi, E. Khanmirza, and K. Daneshjou: "Hybrid force/position control of robotic arms manipulating in uncertain environment based on adaptive fuzzy sliding mode control", *Applied Soft Computing* (2018)

https://doi.org/10.1016/j.asoc.2018.05.048.

(26) A. Šabanović and K. Ohnishi: *Motion control systems*, John Wiley & Sons, Singapore (2011)

(27) K. Ohishi, K. Ohnishi, and K. Miyachi: "Torque-speed regulation of DC motor based on load torque estimation", in *Proceedings of the IEEJ International Power Electronics Conference*, Vol.2, pp.1209–1216 (1983)

(28) T. Murakami and K. Ohnishi: "Observer-based motion control-application to robust control and parameter identification", in *Proc. Asia-Pacific Workshop on Advances in Motion Control*, pp.1–6 (1993)

(29) K. Ohnishi, M. Shibata, and T. Murakami: "Motion control for advanced mechatronics", *IEEE/ASME Trans. Mechatronics*, Vol.1, No.1, pp.56–67 (1996)

(30) T. Murakami, F. Yu, and K. Ohnishi: "Torque sensorless control in multidegree-of-freedom manipulator", *IEEE Trans. Ind. Electron.*, Vol.40, No.2, pp.259–265 (1993)

Tarik Uzunovic (Non-member) received the B.Eng. and M.Eng. degrees in electrical engineering from the University of Sarajevo, Sarajevo, Bosnia and Herzegovina, and Ph.D. degree in mechatronics from Sabanci University, Istanbul, Turkey, in 2008, 2010, and 2015, respectively. He is an Assistant Professor with the Department of Automatic Control and Electronics, Faculty of Electrical Engineering, University of Sarajevo, Sarajevo, Bosnia and Herzegovina. His research interests include motion control, robotics, and mechatronics.

Asif Sabanovic (Non-member) received the B.S., M.S., and Dr.Sci. degrees in electrical engineering from the University of Sarajevo, Sarajevo, Bosnia and Herzegovina, in 1970, 1975, and 1979, respectively. He is an Emeritus Professor at Sabanci University, Istanbul, Turkey. From 1970 until 1991, he was with Energoinvest - Institute for Control and Computer Sciences, Sarajevo. In 1991, he was with the Department of Electrical Engineering, University of Sarajevo. He was a Visiting Researcher with the Institute of Control Sciences, Moscow, Russia, Visiting Professor with the California Institute of Technology - CALTECH, Pasadena, Hitachi Chair Professor with Keio University, Yokohama, Japan, Full Professor with Yamaguchi University, Ube, Japan, Head of CAD/CAM and Robotics Department at Tubitak - Marmara Research Centre, Istanbul. His research interests include control systems, motion control systems, robotics, mechatronics, and power electronics.

Minoru Yokoyama (Student Member) received the B.E. and M.E. degrees in electrical and computer engineering from Yokohama National University, Yokohama, Japan, in 2015 and 2017, respectively. He is currently working toward the Ph.D. degree at Yokohama National University. His research interests include mechatronics, motion control and haptics.

Tomoyuki Shimono (Senior Member) received the Ph.D. degree in integrated design engineering from Keio University, Yokohama, Japan in 2007. From 2007 to 2008, he was a Research Fellow of the Japan Society for the Promotion of Science. From 2007 to 2008, he was also a Postdoctoral Fellow at Keio University. From 2008 to 2009, he was a Research Associate with the Global Centers of Excellence Program, Keio University. Since 2009, he has been with the Department of Electrical and Computer Engineering, Yokohama National University, Yokohama, where he is currently an Associate Professor. His research interests include haptics, motion control, medical and rehabilitation robots, and actuators.