Optimal Control of a Robotic System for Human Power Enhancement

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Abstract

Human power augmentation devices are robotic systems used for assisting the operator in the execution of manipulative/walking tasks and with the capability of amplifying human force. In this paper we present a new approach for the synthesis of an LQG controller that, with respect to other solutions, does not require direct measurements of interaction forces between the robotic device and the external environment. The experimental performance of the devised controller is shown on a testbed with 1 DOF.

1. Introduction

EHPA (Enhanced Human Power Augmentation) is referred to as an ambitious project which was started in the 1990s, aimed at developing wearable robotic interfaces which could artificially augment the human strength by means of supporting arm and leg muscles [1]. Such systems are peculiar force feedback interfaces which can be used for the accomplishment of massive effort demanding tasks as well as for rehabilitation purposes: the operator only feels a scaled-down version of a manipulated load or requires only a fraction of the normally required effort to perform a task.

The first attempt towards the creation of an exoskeletrical system which could enhance the human power goes back to the early 1960s, when General Electric developed *Hardiman* [2], a robotic system which could allow the user to carry loads up to 750kg with a force amplification ratio of 25:1. The system was based on a master-slave architecture, with an inner electrical exoskeleton which controlled an outer hydraulic exoskeleton.

Many prototypes of human power augmentation systems have been developed in the last years. *HAL* (Hybride Assistive Limb), a lower-limb-strengthening device, has been developed at the Tsukuba University in 2004 [3]. It is controlled by a hybrid predictive approach, based on two modules: a position controller, which operates according to the "phase sequence" method, and a force controller regulating the actuator torque from the myoelectric signals coming from the muscles involved during locomotion. *Power Exoskeleton* [4] is another example of lower-limb-strengthening devices. It was developed by Sarcos in 2004 and is driven by piezo-hydraulic actuators. *Arm Extender* (1996) and *BLEEX* (Berkeley Lower Extremity EXoskeleton, 2004, [5]), both developed at Berkeley University, are separate upper- and lower-limb-strenghtening devices. The control algorithm is based on an inner stabilizing position or velocity controller.

A full body exoskeleton system is currently under development at PERCRO laboratory in the framework of a research project funded by the Italian Ministry of Defense. A schematic view of the actual mechanical design of the system is shown in Figure 1.

Figure 1 – The PERCRO Body Extender design

The main project goal is to build a device able to enhance human physical performance in logistics applications within an unstructured environment, i.e. increasing the possibility of heavy load movimentation for an operator. This goal should be achieved guaranteeing high dexterity while performing the task, high flexibility in terms of allowable postures and high transparency of the system for the operator who uses it.

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The control problem for exoskeleton devices could be regarded to some extent conceptually similar to teleoperation systems, presenting however an asymmetric scheme, since typically only forces are scaled-up by an amplification factor, while positions are mapped with a 1 to 1 scheme.

An output feedback controller for force amplification is presented in [7]. The main idea underlying this control algorithm is to have an internal stabilizing position or velocity loop to guarantee major overall system robustness and safety, and an additional external force control which performs the real force multiplication. The proposed algorithm involves a direct measure of the interaction forces both at the human-interface and at the interface-environment sides, which may limit its applicability. In fact, while there no significant problems related to the measurement of position and velocity variables, which can easily be derived respectively by means of rotary position sensors at joint/motor shafts and indirectly estimated by the position signals, there are major problems related to the measurement of force signals.

At least one force sensor is necessary in order to measure the interaction force between the human operator and the robotic structure. The use of a second force sensor to measure the interaction force at the environment side, allowing to achieve a better performing closed loop system, presents unfortunately some implementation problems: the requirements of compactness and non-invasivity for an external sensing element are more difficult to fulfill, and the range of forces to be measured and required stiffness performance are dependent on the manipulated load, usually scaled-up by a factor α with respect to the human operator acting force.

In this paper we propose a new methodology for the synthesis of optimal controllers for human power enhancement systems, based on an LQG scheme, that does not require force sensing toward the environment.

In section 2 the state space representation of a force amplification device with 1 DOF is presented. Section 3 and Section 4 present respectively the synthesis of a Kalman filter for the estimation of environment force and of an LQR controller. In Section 5, the preliminary experimental results obtained so far on a 1DoF test bench are presented. Finally, conclusions and further research perspectives are summarized in Section 6.

2. Problem statement

A human power enhancement device can be described as a robotic structure containing a set of joints which operate concurrently to help a user to perform desired tasks by actively amplifying his physical strength. The required bandwidth of such systems can be quite low, i.e. around 5Hz, and the transmission ratios within the structure may conversely be thought as extremely high. Under these assumptions, a *decentralized control* may be applied to the joints and the dynamic behavior of a single joint can be assumed to be representative for the behavior of the complete structure [6]. A 1DoF interface has therefore been studied as a significant testbed for the control application. The conceptual scheme of a simple 1DoF force amplification interface is presented in Figure 2.

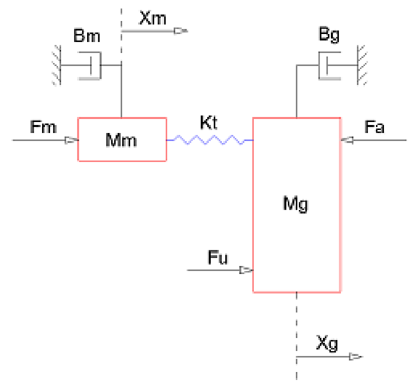

Figure 2 - Conceptual scheme of a 1DoF force amplification interface

A human operator and environmental forces act directly on a central mass – or central joint – by means of two forces referred to as F_u and F_a. The joint is modeled as having inertia M_g, and a velocity damping coefficient B_g; its position is denoted by X_g. An electric actuator acts on the joint as well by means of an elastic transmission modeled as a spring with stiffness K_t. The control command F_m is applied to the actuator (inertia M_m, damping coefficient B_m, position X_m) and transferred to the joint by means of the elastic transmission.

The human is required to maintain the mass at rest or move it at a desired speed by contrasting to the action of the environment force F_a. The goal of the control algorithm to be synthesized is to guarantee proportionality between F_u and F_a, i.e. $F_a = \alpha F_u$. The constant factor α is called *force amplification ratio*, due to the fact that the human operator only applies a fraction of the required force to perform a task, and the lacking force is supplied by the actuator. The action of the motor is aimed at helping the human operator while performing the task, providing the necessary additional force. The main parameter which can be used to evaluate the controller efficiency is the difference between F_a and αF_u, which should be equal to zero in a specified range of frequencies (e.g.: 0-5Hz) within which the most relevant human arm movements occur.

The equations describing the system dynamics are as follows:

$$\begin{cases} M_g \ddot{X}_g = F_u - F_a + K_t(X_m - X_g) - B_g \dot{X}_g \\ M_m \ddot{X}_m = F_m - K_t(X_m - X_g) - B_m \dot{X}_m \end{cases} \quad (1)$$

Choosing $X = [X_m \quad \dot{X}_m \quad X_g \quad \dot{X}_g]^T$ as state vector and $u = [F_m \quad F_u \quad F_a]^T$ as input vector, the following state-space representation of the dynamics of the model can be written as:

$$\begin{cases} \dot{X} = AX + Bu \\ Y = CX + Du \end{cases} \quad (2)$$

where:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{K_t}{M_m} & -\frac{B_m}{M_m} & \frac{K_t}{M_m} & 0 \\ 0 & 0 & 0 & 1 \\ \frac{K_t}{M_g} & 0 & -\frac{K_t}{M_g} & -\frac{B_g}{M_g} \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{M_m} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{M_g} & -\frac{1}{M_g} \end{bmatrix} \quad (4)$$

C and D matrices may be built after the definition of the sensed variables.

3. Kalman filter

The lack of force sensing at the level of the environment could strongly limit the performance which can be obtained with an output feedback controller, because the environment mechanical impedance may vary a lot within a wide range defined within the system specifications, and no direct information about the environment dynamics is available without a sensor. Moreover such information is explicitly required in the formulation of any classical output feedback controller. Without this direct information from the environment side the controller may be optimized around *one single* working condition, and cannot be sufficiently robust in terms of performance within the whole range of variation for the environment mechanical impedance.

In this section, we present the design of a Kalman filter, specifically devised to provide an indirect estimation of the interaction force between the interface and the environment.

The model presented within Section 2 must be slightly modified in order to carry out a force estimation, by including the variable F_a in the state vector as an extended state. Under this assumption, the expression of the time derivative of F_a is not expressible in terms of the other (kinematic) state variables.

To overcome this issue, we have followed the approach presented in [8], where a torque disturbance with unknown dynamics acting upon a motor shaft is estimated by modeling such variable as not depending on any of the state or input variables, but considering its time derivative as being affected by a Gaussian white noise with large covariance.

Such approach can be easily applied to the 1DoF interface examined in Section 2, modifying the system state space representation by adding an augmented state $X' = \begin{bmatrix} X & F_a \end{bmatrix}^T$ and a reduced input vector $u' = [F_m \quad F_u]^T$. As in 8, the time derivative of F_a is considered affected by a white noise with large covariance. Under these assumptions, the system dynamics in (2) can be rewritten as:

$$\begin{cases} \dot{X}' = A'X' + B'u' + \Gamma w \\ Y = C'X' + D'u' + v \end{cases} \quad (5)$$

where:

$$A' = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\frac{K_t}{M_m} & -\frac{B_m}{M_m} & \frac{K_t}{M_m} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ \frac{K_t}{M_g} & 0 & -\frac{K_t}{M_g} & -\frac{B_g}{M_g} & -\frac{1}{M_g} \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

$$B' = \begin{bmatrix} 0 & \frac{1}{M_m} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{M_g} & 0 \end{bmatrix}^T \quad (7)$$

$$\Gamma = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{M_g} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T \quad (8)$$

The vector w is a 2-dimensional process noise vector which is assumed to be a zero-mean, Gaussian distributed, random noise process with a diagonal 2x2 covariance matrix Q. On the other hand, v is a kinematic variables measurement noise vector with a diagonal covariance matrix R. The size of the matrix R depends on the number of variables used in the synthesis of the Kalman filter. The process noise and the measurement noise are assumed to be uncorrelated.

In order to build the Q and R matrices, noise data should be provided. While the force sensor noise can be easily estimated from experimental measurements

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of the sensor placed in a rest position with no load applied, encoder noise variance can be estimated according to the expression [9]:

$$\operatorname{var}\left(\theta_m\right) = \frac{\theta_r^2/4 + 2r}{3} \tag{9}$$

where θ_r is the encoder resolution and r is the variance associated to the quantization error.

The last variance is the characterization of the noise of the time derivative of F_a. Due to the fictitious value of this variance, its choice is not trivial: in fact, a very high value of the parameter yields to an extremely noisy estimation of F_a, whereas a low value yields to a poor estimation of the same variable. A careful trade-off depending on the available platform is therefore to be examined before synthesizing the controller.

4. LQR control

The accurate estimation of the augmented state X' can be used to perform a state-feedback control after computing an appropriate gain matrix with a modified LQR technique. To solve a standard LQR problem, there is the need to define a quadratic cost function $J = \int\left(x^T Q x + u^T R u\right)dt$ (where x is the state vector and u is the input vector) to be minimized. Q and R are weighing matrices permitting to express the cost function in terms of state and input variables.

In order to write an adequate cost function realizing the target of guaranteeing the desired proportionality between F_u and F_a, the model (5) could be extended to consider interaction forces F_u and F_a as part of the state vector.

The operator and the environment apply forces onto the joint M_g in different points. Two high-stiffness elastic elements K_{su} and K_{sa} are placed between the real application point of F_u and F_a and the position considered as the reference application point for both forces when having a rigid joint M_g. If the mechanical properties K_{su} and K_{sa} respectively of the sensor placed at the human side and of the links used for transmitting the force at the environment are estimated, the position variables X_u and X_a, i.e. the real human and environment positions, can be assumed as independent variables, while forces F_u and F_a can be expressed as:

$$F_u = K_{su}\left(X_u - X_g\right) \tag{10}$$

$$F_a = K_{sa}\left(X_a - X_g\right) \tag{11}$$

The model (2) can therefore be updated again in order to be put in a suitable form for a LQR control synthesis. The most important changes involve the state vector X and the input vector u. The former can be extended to a 6-element vector containing both F_u and F_a:

$$X'' = \left[X \quad F_a \quad F_u\right]^T \tag{12}$$

On the other hand, the expression of the input vector can be modified as follows:

$$u'' = \left[F_m \quad \dot{X}_a - \dot{X}_g \quad \dot{X}_u - \dot{X}_g\right]^T \tag{13}$$

Hence, a different representation of the system dynamics which is functional to the control synthesis can be written as follows:

$$\dot{X}'' = A'' X'' + B'' u'' \tag{14}$$

where:

$$A'' = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{K_t}{M_m} & -\frac{B_m}{M_m} & \frac{K_t}{M_m} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \frac{K_t}{M_g} & 0 & -\frac{K_t}{M_g} & -\frac{B_g}{M_g} & -\frac{1}{M_g} & \frac{1}{M_g} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{15}$$

$$B = \begin{bmatrix} 0 & \frac{1}{M_m} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & K_{sa} & 0 \\ 0 & 0 & 0 & 0 & 0 & K_{su} \end{bmatrix}^T \tag{16}$$

It is important to emphasize that the choices presented in (12) and (13) go beyond the classical interpretation of state and input variables for a dynamical system. The differential equations describing the system are valid and independent from the classification of a physical variable as a state or input variable. As a matter of fact, the input variable $\left(\dot{X}_u - \dot{X}_g\right)$ is not a controllable physical variable, since there is no actuator capable of directly controlling this input.

The values within the matrix R have to be chosen according to the physical limitation deriving from having only one controllable input to the system, i.e. F_m. Hence, an appropriate choice of the matrix R should enable the construction of a LQR gain matrix which strongly penalizes the last two non-controllable inputs in favour of the real input F_m. Hence, the structure of the R matrix, that should be non-singular, can be as follows:

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \lambda_m & 0 \\ 0 & 0 & \lambda_g \end{bmatrix} \tag{17}$$

where $\lambda_m, \lambda_g \gg 1$.

The actual implementation of the controller will represent so a good approximation of the theoretical solution achievable with the LQR synthesis, only if the

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action required to the non-controllable inputs would result to be negligible.

The values within the matrix Q can be chosen according to the mathematical formulation of important quantities to be minimized:

Force amplification error: this is the key feature of the control system, which can be evaluated considering the difference between the value of F_a and the value of F_u multiplied by the force amplification ratio α. Thus, the quantity to be minimized has the following structure: $\beta\left(F_a-\alpha F_u\right)^2$

Transmission vibrations: to avoid resonance phenomena related to the elastic transmission. The quantity to be minimized can be expressed in terms of joint and actuator velocities: $\gamma\left(\dot{X}_m-\dot{X}_g\right)^2$

Joint and actuator velocities: it is important to limit joint and actuator velocities in order to guarantee higher system stability margins. The quantity to be minimized has the following structure: $\delta_m\dot{X}_m^2+\delta_g\dot{X}_g^2$

After some algebraic computation, the following form for matrix Q can be found:

$$Q=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \gamma+\delta_m & 0 & -\gamma & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\gamma & 0 & \gamma+\delta_g & 0 & 0 \\ 0 & 0 & 0 & 0 & \beta & -\alpha\beta \\ 0 & 0 & 0 & 0 & -\alpha\beta & \beta\alpha^2 \end{bmatrix} \quad (18)$$

An optimal combination of the factors β, γ, δ_m and δ_g can be found after choosing the relative importance of the described criteria.

A final note should be addressed to the fact that the first five components of the new state vector to be multiplied by the LQR matrix derive from the Kalman filter, whereas the sixth variable, F_u, is directly read from the human side force sensor.

5. Experimental results

The proposed strategy to synthesize a state-space controller able to perform the required power multiplication has been tested using the simple test bench with one rotational degree of freedom shown in Figure 3.

By means of an appropriate handle, a human operator pulls a beam in order to lift a load which is attached to the beam itself. The beam has one rotational degree of freedom around a shaft and pulley system. A remotely located electric actuator on the same shaft through an elastic transmission and helps the human operator while performing the task. A force sensor is mounted between the handle and the beam, and the motor position is recorded by means of an optical incremental encoder as well as the position of the shaft to which the beam is attached.

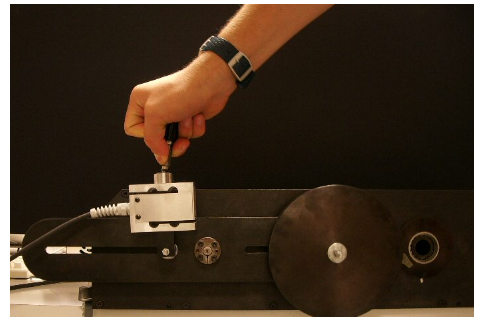

Figure 3 - 1DoF test bench

An initial parameter identification phase has been carried out in order to measure the model parameters. Motor and joint inertias have been computed using a CAD model of the interface, whereas damping coefficients as well as transmission elasticity had to be measured through an experimental investigation. Force balancing and energy balancing equations have been used to evaluate these parameters. Dynamic responses for free motion from a known initial position-velocity state and for motion under the application of a known exciting torque have been evaluated. Moreover, the elastic transmission rigidity has been evaluated by blocking the joint, applying a known torque to the actuator, and measuring the displacement on the actuator axis. Values for stiffness K_{su} and K_{sa} have been estimated from measured stiffness of the force sensor and estimated stiffness of the beam of the testbed, according to its material and section geometric properties.

A Kalman filter has been synthesized for the system with the method presented in Section 3. The quality of position tracking is shown in Figure 4, where the compensation of the encoder quantization is shown. The delay introduced into the system due to the filter presence is negligible.

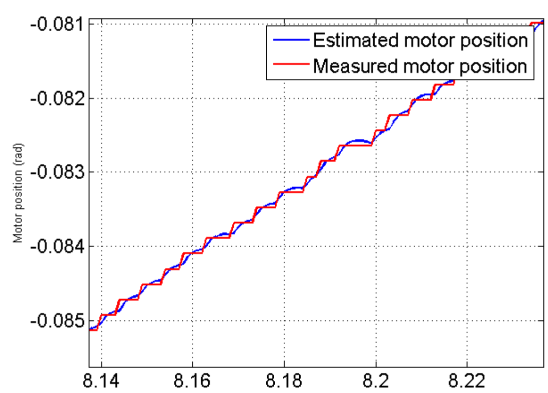

Figure 4 – Motor position estimation

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Moreover, the quality of the environment torque estimation is shown in Figure 5, where the estimated environment torque is compared to the sum of the instant torques applied by the human and the motor while moving the load.

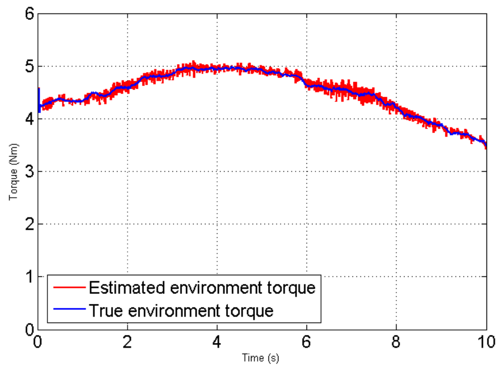

Figure 5 - Environment force estimation

A LQR controller has been synthesized with the method presented in Section 4, and adequate coefficients have been chosen to build matrices Q and R. The obtained gain matrix had negligible elements on the second and on the third row, i.e. the second and third inputs were not used to guarantee the system performances. The synthesized controller is able to maintain the desired force amplification ratio (α=5) in quasistatic conditions, i.e. with a slowly moving load, as shown in Figure 6.

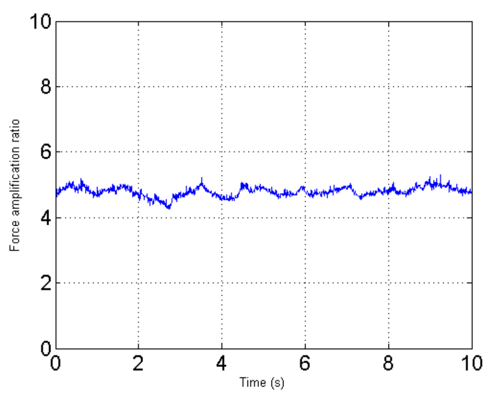

Figure 6 - Force amplification ratio - quasistatic conditions

However, the significance of the LQR approach is much more relevant in dynamic conditions, for example when sudden high amplitude sinusoidal inputs are applied by the operator (e.g. due to sudden bad balance conditions while carrying the load). As shown in Figure 7, the system does not suddenly amplify the force read from the force sensor but behaves in order to guarantee better system stability, compensating so the internal modelled dynamics of the system. A trivial open loop control would have instead required the operator to virtually close the control loop adapting in order to guarantee the system stability in potentially unstabilizing circumstances.

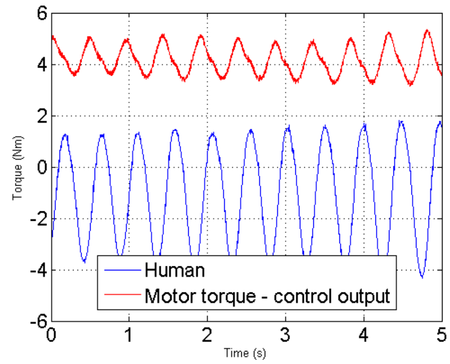

Figure 7 - LQR - dynamic conditions

6. Conclusion

This paper has presented a novel approach for the synthesis of an LQR control for human power augmentation. The control does not require direct force measurements at the environment side. The performance of the proposed controller has been experimentally evaluated through a 1DOF testbed. The proposed controller allows to achieve an active compensation of system dynamics and to preserve a stable value of the amplification force ratio.

References

[1] Garcia E. et alia, *Exoskeletons for human performance augmentation (EHPA): a program summary*, Journal of the Robotics Society of Japan, vol. 20, n. 8 (2002)

[2] Mosher R., *Handyman to Hardiman*, Society of Automotive Engineers, New York (1967)

[3] Kawamoto H. et alia, *Power assist method for HAL-3 estimating operator's intention based on motion information*, Proceedings of IEEE ROMAN 2003

[4] http://www.sarcos.com

[5] http://bleex.me.berkeley.edu

[6] Sciavicco L., Siciliano B., *Modelling and control of robot manipulators*, Springer Verlag, 2nd ed., 2001

[7] Kazerooni H., *Human-robot interaction via the transfer of power and information signals*, IEEE Trans. on Sys., Man and Cybernetics, vol. 20, n. 2, March/April 1990

[8] Heui-Wook Kim, Seung-Ki Sul, *A new motor speed estimator using Kalman filter in low-speed range*, IEEE Trans. on Industrial Electronics, vol. 43, n. 4 (1996)

[9] Belanger P. R., *Estimation of angular velocity and acceleration from shaft encoder measurements*, Proceedings of IEEE ICRA 1992

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