

# Virtual Reference Feedback Tuning (VRFT) of velocity controller in self-balancing industrial manual manipulators

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**Abstract** – Self-balancing manual manipulators are devices that countervail the weight of a load that must be manually handled and moved by a human operator. An electric motor delivers the force needed to control the velocity of a spool with a metallic rope to which the load is hanged. This work concerns the tuning of the DC electric motor velocity controller. Specifically, Virtual Reference Feedback Tuning has been applied, which provides controller parameter tuning in a completely automatic way based on a single I/O batch measurement on the plant. The tuned controller shows good tracking performances and good robustness to variation in the applied load.

## I. INTRODUCTION AND PROBLEM STATEMENT

Self-balancing manual manipulators are devices devoted to help human operators in manually handled heavy loads. Such a system is composed by a mechanical structure, that can be very different depending on the application, and a controlled DC electric motor fixed to it and moving a spool with a metallic rope lifting the load. A self-balancing manual manipulator is able to balance the weight of a load, so that a human operator can manually handle and move it as it is virtually weightless. These devices are used in many different industrial applications where no specific constraints on the work speed or on the precision of the positioning are required. However, since they are directly manually operated, they have both the flexibility of a human operator and the power of a machine.

Recently, as a return of a joint research project of University of Bergamo, Politecnico di Milano and Scaglia Indeva R&D unit, a closed-loop velocity controller for the electric motor has been developed. Previously, balancing was controlled in

open-loop mode on the basis of the load weight, measured by a load cell. The design of the closed-loop controller presents also a tuning issue: each manipulator controller must be tuned at the end of the production line to obtain the best performance. This is necessary because of the system dynamics that can be quite different among different devices, mainly due to the tolerances of the mechanical assembly, which can determine significant variations of the friction, and to the customization for the end-user. So, an autotuning procedure, to be performed at the end of the production line in a completely automatic way, is strongly advisable. Moreover, an auto-tuning procedure can be made available to the end-user as a maintenance add-on.

In the present work, a direct control design approach will be used: the *Virtual Reference Feedback Tuning* (VRFT) strategy, which allows the tuning of a feedback controller without resorting to a model of the plant. Moreover, the VRFT method needs only a single set of I/O data to provide the solution to the problem of designing a controller for system with unknown I/O relationship. This is the major difference with respect to other direct control design techniques (see for instance Iterative Feedback Tuning -IFT [8,9]). The VRFT algorithm is strongly appealing in view of the design of an end-of-line auto-tuning procedure of the self-balancing control algorithms and, in general, in any industrial applications. The basic idea of the VRFT was originally proposed in [14] and developed in [6,7,15]. Then, it has been realized in its final form, used in this paper, in [2,3,4,5] as a complete and ready to use method for data-driven control design in a noisy environment. Finally, VRFT has been successfully applied to a number of applications,

from automotive [4] to biomedical control problems [12,13]. The paper is organized as follows: in Sect. 2 the experimental set up is outlined and the architecture of the control system is described. Sect. 3 is devoted to short description of the VRFT approach and the experimental results are presented in section 4.

## II. EXPERIMENTAL SETUP

A schematic representation of the device considered in this paper is shown in Fig. 1 (a picture is shown in Fig. 2). The manipulator consists of three main parts:

- a mechanical structure, specifically designed for the operating needs of the end-user. In the present paper, we considered a freestanding column with a folding arm (other different supports are available such as, ceiling support, overhead rails or jibs). The fully extended arm is 2.5 m long and the column height is 2.43 m.
- a DC brushed electric motor (about 1 kW power) fixed to the structure and connected to the metallic rope spool through a transmission gear. Rotation speed is measured by an encoder positioned on the spool rotation shaft. The motor is endowed with an embedded closed loop current controller with large bandwidth. The manipulator considered in this paper is designed to lift a maximum load of 80 kg.
- a handle, where the load is hooked, positioned at the end of the rope. The handle is a complex mechanical device endowed with a load cell which measures the forces delivered by a human operator decoupling it by the hanged load. The handle can be equipped by many different lifting tools. The experiments in this work have been performed using a hook. The total weight, including handle and hook, is about 7 kg.

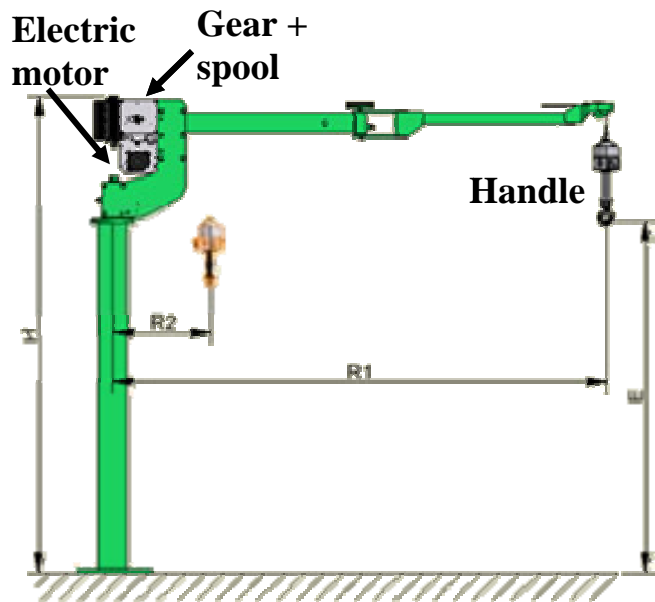


Fig. 1. A schematic representation of the device used in this work.



Fig. 2. Example of operating condition of the device in food industry

Before the development of the present research project, the electric motor was driven in *open loop* (see Fig. 3). The current driving the motor was the sum of two contributions:

- the first one, namely  $i_{bal}$ , is proportional (through  $k_{bal}$ ) to the load measurement. It is a *balancing current*, since its effect is the generation by the motor of a torque value to lift and keep still the load.
- The second one, namely  $i_{mov}$ , is proportional (through  $k_{mov}$ ) to the handle load cell measurement and it produces an additional torque to move the load.

The electric motor, fed by the total current  $i_{tot}$ , produces a total torque  $T_{tot}$ : part of it compensate the load and the remaining part is the motor torque  $T_{mov}$  that sets the motor  $M$  rotation speed  $\omega$ .

As evident from Fig. 3, this open loop architecture is a standard open loop compensation of a measurable load disturbance [16]. During preliminary tests on the manipulator we experienced low robustness to measurement noise. This drawback is only partially compensated by the large static friction of the motor-gear-spool system and occasionally some device could present spontaneous undesired drift motion.

For these reason a new *closed loop* control system has been designed according to the scheme of Fig. 4. The load disturbance compensation is provided by a closed-loop velocity 1-DOF controller  $C_v$ , based on the rotation speed measure  $\omega$  provided by the encoder. So, a measurement of the load is no more necessary and the load sensor can be removed. The reference signal  $\omega_{ref}$  of the velocity control loop is generated by suitable filtering of the handle load cell measure. This control architecture is intrinsically more robust to any external disturbance and in particular to load disturbances without any need of measuring it. For the

tuning of the velocity controller we resort to VRFT approach, which is a completely automatic tuning procedure and is based on a single batch I/O measurement performed on the plant. In this way, the tuning can be done at the end of the production line quickly and without human direct intervention. It is worth noting that the proposed procedure

can be also applied during the manipulator life-time, if some significant modification of its dynamical behavior occurs (for instance, dynamic friction reduction, changes in the motor efficiency, etc...).

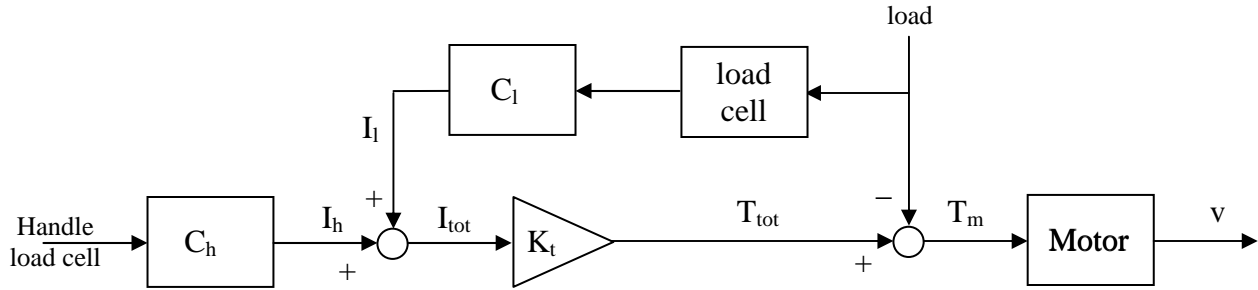


Fig. 3. Representation of the “old” open-loop control architecture.

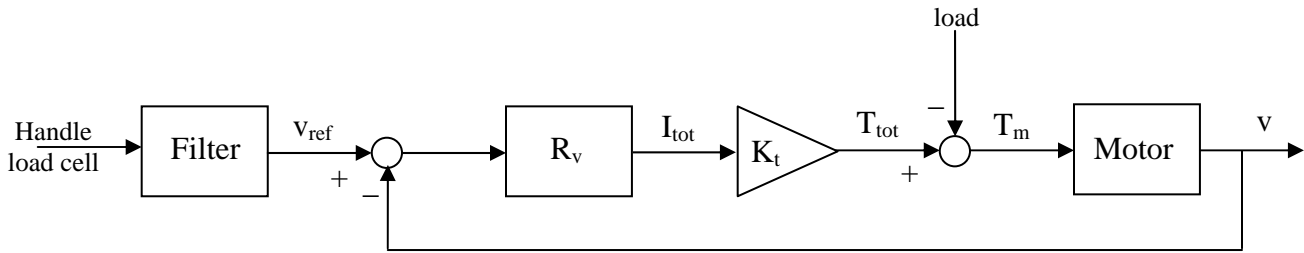


Fig. 4. Representation of the “new” closed-loop control architecture. Notice that the load cell, devoted to the load measure, disappeared.

### III. VIRTUAL REFERENCE FEEDBACK TUNING

The VRFT strategy approximately solves a model-reference problem in discrete time. The control specifications are assigned via a reference model which describes the desired behavior of the closed-loop system. The reference model is given in terms of a transfer function  $M(q)$ , being  $q^{-1}$  the unit delay operator. This model is used to define in a simple and effective way the basic characteristics of the closed-loop control system such as its settling time, the allowed overshoot etc. Typically, a first or second order model allows a complete specification of the closed loop performances.

The VRFT approach allows a “one-shot” tuning of a linear controller, i.e. the controller parameters are directly derived from a single batch of data without any specific action by the designer. This feature is very useful in the present application. In fact, using the VRFT algorithm, the end-of-line tuning of the controller can be performed in a very short time with great benefits for productivity. Mainly for this reason, the VRFT approach is preferable with respect to other more time-consuming direct design strategies (such as

Iterative Feedback Tuning, as an example [8,9]).

In the VRFT approach the following closed-loop system is considered:

$$y(t) = P(q)u(t) \tag{1.1}$$

$$u(t) = C(q; \theta)(r(t) - y(t)) \tag{1.2}$$

The plant is described by its unknown transfer function  $P(q)$  and  $C(q; \theta)$  is the transfer function of a one-degree-of-freedom controller belonging to a given family of linear transfer function controllers  $\{C(q; \theta)\}_{\theta \in \mathbb{R}^n}$  parameterised by the  $n$ -dimensional real vector  $\theta$ . The signals  $u(t)$  and  $y(t)$  are respectively the input (the control action) and the output of the considered plant (assumed to be scalar). The signal  $r(t)$  is the reference signal of the control loop. The closed loop system dynamics is characterized by the transfer function from  $r(t)$  to  $y(t)$ :

$$y(t) = \frac{P(q)C(q; \theta)}{1 + P(q)C(q; \theta)} r(t) \tag{2}$$

Let us assume that a set of I/O data  $\{u(t), y(t)\}_{t=1, \dots, N}$  has been collected during an experiment on the plant and that a reference model  $M(q)$  has been chosen on the basis of the

desired closed-loop behavior. If the plant model  $P(q)$  were known, the controller  $C(q; \theta)$  could be designed, i.e. a value for the parameter  $\theta$  could be estimated, by solving the following model reference problem:

$$\bar{\theta} = \arg \min_{\theta} J_{MR}(\theta) \quad (3. a)$$

where

$$J_{MR}(\theta) = \left\| \frac{P(z)C(z; \theta)}{1 + P(z)C(z; \theta)} - M(z) \right\|_2^2 \quad (3. b)$$

By means of VRFT, it is possible to solve approximately this problem without knowledge of the plant transfer function. The idea is to transform the Model Reference (MR) problem into a Virtual Reference (VR) one, which can be proven to be approximately equivalent to the first one under mild conditions.

To this aim, given the measured  $y(t)$  (i.e. the actual signal measured at the output of the plant), consider a *virtual reference*  $r_v(t)$  such that  $M(q)r_v(t) = y(t)$ . Such a reference is called *virtual* because it does not exist in reality (it is not used in the generation of  $y(t)$ ). In this framework,  $y(t)$  is the desired output of the closed-loop system when the reference signal is  $r_v(t)$  and the corresponding *virtual tracking error* is  $e_v(t) = r_v(t) - y(t)$ . Therefore, a good controller must generate  $u(t)$  when fed by  $e_v(t)$ , as an effect of the application of the *virtual reference*  $r_v(t)$ : the idea is to search for such a controller.

Since both signals  $u(t)$  and  $e_v(t)$  are known, this task is reduced to the “*identification problem*” of describing the dynamical relationship between  $e_v(t)$  and  $u(t)$  by using the family of linear models  $\{C(q; \theta)\}_{\theta \in \mathbb{R}^n}$ , i.e. estimating

$$\hat{\theta} = \arg \min_{\theta} J(\theta) \quad (4. a)$$

by minimizing the following cost function

$$J(\theta) = \frac{1}{N} \sum_{t=1}^N (u(t) - C(q; \theta)e_v(t))^2 \quad (4. b)$$

Obviously, minimization of the cost function (4) is not equivalent to minimization of the original MR cost function (3). However, in [2] it is proven that a filter  $L(z)$  can be designed so that the MR criterion (3) can be matched by means of the criterion (4) applied to filtered version of  $u(t)$  and  $e_v(t)$  (specifically, the minimum arguments of both the criteria can be made as close as possible – even identical in ideal conditions).

In the following, the algorithm implementing the above idea is briefly outlined. In the algorithm, the identification of the controller is addressed by minimizing the classical least-squares identification criterion (see [1,11]).

Given the reference model  $M(q)$ , the family of controllers  $\{C(q; \theta)\}_{\theta \in \mathbb{R}^n}$  and the set of data  $\{u(t), y(t)\}_{t=1, \dots, N}$  apply the following procedure:

1. Calculate:

- a virtual reference  $r_v(t)$  such that  $y(t) = M(q)r_v(t)$ , and

- the corresponding virtual tracking error

$$e_v(t) = r_v(t) - y(t).$$

2. Filter the signals  $e_v(t)$  and  $u(t)$  with a suitable filter  $L(q)$ , obtaining:

$$e_L(t) = L(q)e_v(t) \quad (5. a)$$

$$u_L(t) = L(q)u(t) \quad (5. b)$$

3. Estimate the controller parameter vector

$$\hat{\theta} = \arg \min_{\theta} J_{VR}(\theta) \quad (6. a)$$

where

$$J_{VR}(\theta) = \frac{1}{N} \sum_{t=1}^N (u_L(t) - C(q; \theta)e_L(t))^2 \quad (6. b)$$

Notice that Eq. (6.b) is quadratic in the parameter vector  $\theta$  and all the computations are directly performed on the measurement data, assumed that the filter  $L(q)$  is given. The optimal filter to be used in the design is

$$L(z) = \frac{M(z)(1 - M(z))}{U(z)} \quad (7)$$

where  $U(z)$  is a model of the input signal such that  $u(t) = U(q)v(t)$  where  $v(t)$  is a white noise with unit variance, so that the power density spectrum of the input can be modeled as  $\phi_u(\omega) = |U(e^{j\omega})|^2$ .

Details on the computation of the filter and the complete development of the algorithm can be found in [2,3,4].

Specifically, in this work, we consider the class of PI controllers, which are known to be very effective in velocity control of DC electric motors [10]. The PI controller transfer function (in continuous time) depends only on two parameters

$$R(s) = K_i \frac{1 + sT_i}{s} \quad (8. a)$$

where  $K_i = \frac{K_p}{T_i}$ , being  $K_p$  the proportional gain and  $T_i$  the integral time constant. The transfer function (8.a), opportunely discretized by backward integration, results in a discrete time controller again depending on two parameters that must be tuned

$$\bar{R}(z) = \bar{K}_i \frac{1 - \bar{T}_i z^{-1}}{1 - z^{-1}} \quad (8. b)$$

Notice that, as already evidenced, since the controller is linear in the parameters  $\theta = [\vartheta_1 \ \vartheta_2] = [\bar{K}_i \ \bar{K}_i \bar{T}_i]$ , the performance index  $J_{VR}(\theta)$  is quadratic in the parameters and an estimate  $\hat{\theta}$  can be easily found.

#### IV. EXPERIMENTAL RESULTS

In order to apply the VRFT algorithm, the first step is the design of an experiment to perform the acquisition of the I/O data set. Experiments have been performed using a load of about 40 kg, a medium weight with respect to the operating range of the manipulator. The input current used is a band limited white noise sequence with frequency limit at 5 Hz. The mean value of the current has been set to the value needed to balance the load, i.e. about 5 A. The output

velocity is the vertical load speed that has been easily computed using the measured spool rotation speed. The measured signals have been sampled with sampling frequency  $f_s = 200 \text{ Hz}$  (see Fig. 5).

The reference model used to compute the virtual reference and to design the filter  $L(z)$  is

$$M(z) = 0.556 \frac{1 + z^{-1}}{1 + 0.111z^{-1}}$$

This transfer function has been obtained by discretization of a first-order continuous time model with unitary gain and a pole in  $\omega = 500 \text{ rad/s}$ . Minimization of the VR cost function ends in the following parameter values (see Eq. 8.2):  $\bar{K}_i = 11.62$  and  $\bar{T}_i = 0.92$ .

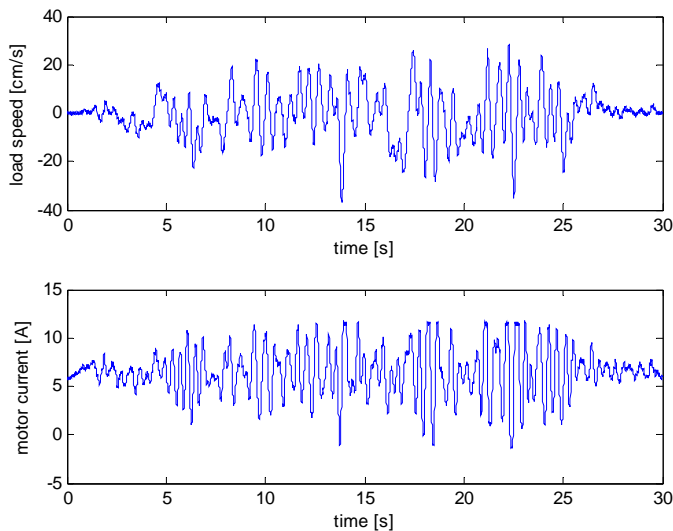


Fig. 5. I/O data set used for the controller tuning

The designed controller has been validated through different experiments. In the first kind of experiments a velocity reference signal has been generated to stress the motor control system. Specifically, the velocity reference signal is composed by: step variations of different amplitude; a ramp signal, both with positive and negative slope; a parabolic signal, both with positive and negative concavity (see Figs. 6,7). This experiment has been performed using light weight (7 kg, Fig. 6) and heavy weight (74 kg, Fig. 7). These experiments show that the controller designed at a medium weight value is robust to weight variations in the operating range of the manipulator (0-80 kg) and it is able to provide good tracking performances at operating regimes different from the design one. Moreover, it is worth noting that the chosen reference signal is really stressing for the machine, with acceleration values that could be hardly generated by a human operator and which are very close to the motor power limit.

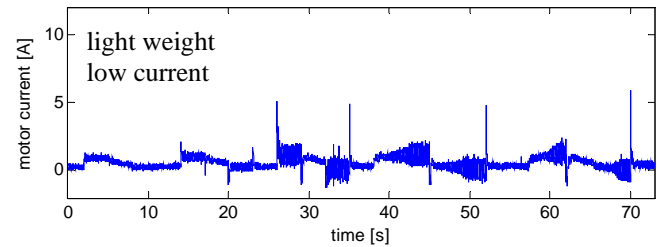
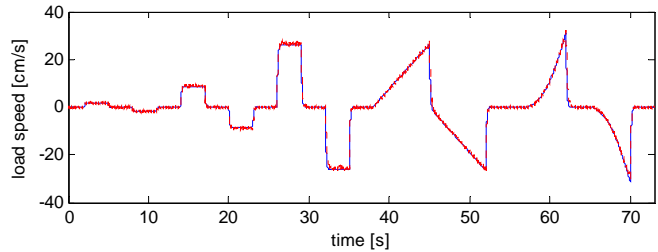


Fig. 6. Tracking experiment with light weight (notice the current mean value in the range 0-1 A).

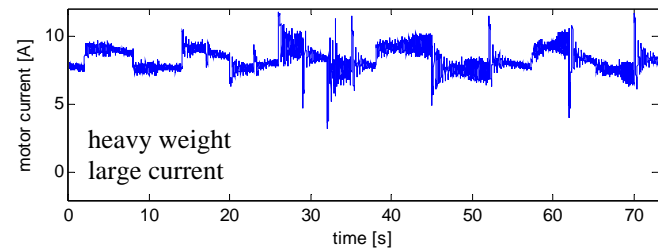
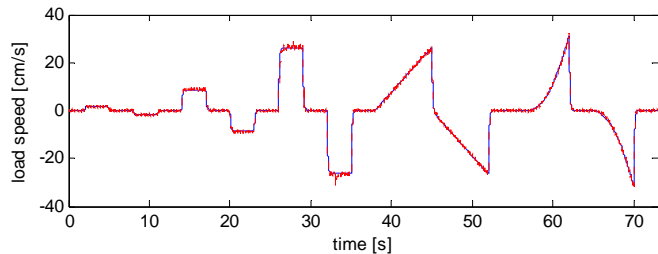


Fig. 7. Tracking experiment with heavy weight (notice the current mean value close to 9-10 A).

An example of the second kind of experiment is shown in Fig. 8: a human operator is manually driving the manipulator in normal operating conditions. In the upper figure, the handle load cell measurement is shown: this is a measure of the force impressed by the operator to the handle, i.e. the desired motion direction and speed. By suitable filtering, from the handle force measure it is possible to generate the velocity reference signal (blue line – middle figure), which is carefully tracked by the control system (red line – middle figure). In the bottom figure it is shown the current supplied to drive the electric motor. Notice that, after about 25 s, the tracking is not perfect since the motor power limit are reached, as evident from the saturation of the current signal. Finally, it is worth doing some remarks about the application of the VRFT algorithm to the present application:

- the VRFT tuning procedure is robust to the use of different realizations of the I/O data (but using the same

reference model and the same load weight): basically, it provides the same parameter tuning (within 5% about the mean values).

- obviously, the application of the algorithm with different load values provides different values of the parameters. If a heavy weight is used to collect the I/O data for the VRFT, the tracking performance will not be very good at light weight because the controller gain will be too large. Similarly, if a light weight is used for the tuning, the control system will result too slow because the controller gain will be too small.
- the controller characteristics, in terms of closed loop response, can be easily driven by the chosen model reference system.

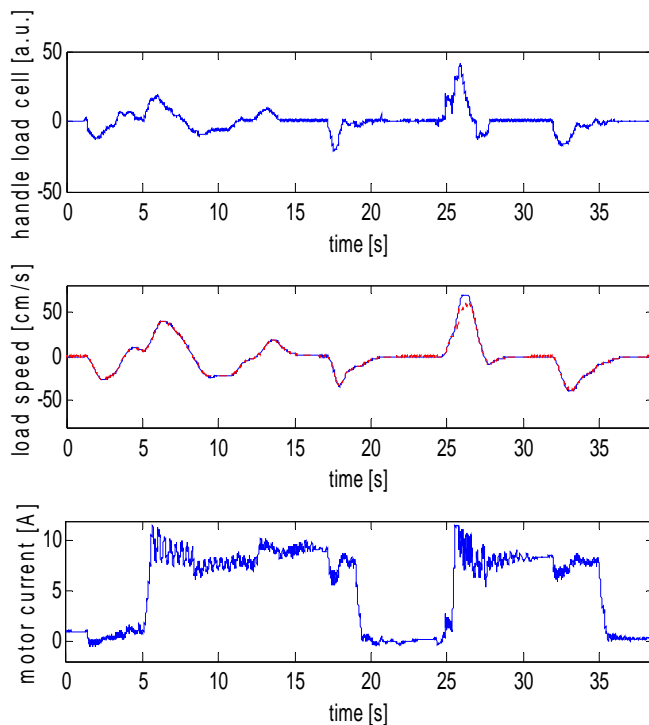


Fig. 8. Tracking experiment in normal operating conditions. The manipulator is driven by a human operator.

## V. CONCLUDING REMARKS

The application of VRFT to the tuning problem of the velocity controller of a DC brushed motor has been successfully completed. The controller shows very good tracking performances and robustness to variations of the operating conditions. The proposed tuning procedure fits the requirements of an end-of-line tuning: it is completely automatic and it is not time consuming, since it can be performed and validated in a very short time, basically the time needed to the acquisition of a single batch of I/O data. Future works could regard the implementation and tuning of a gain-scheduling velocity controller, where the scheduling variable can be obtained by filtering of the current signal or on an estimation of the load weight. Such a controller should provide further increase of the tracking performance in

extreme operating conditions (i.e. no-load or overload weight).

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