Force Sensor-Less Power Assist Control for Low Friction Systems

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Abstract—Nowadays aging population is increasing in many country. As a consequence power assist devices are growing in importance. Knowing the force that the user applies is a key aspect in the control of these devices. Force sensors are often used, even though they are generally expensive, heavy and characterized by time delay. To overcome these aspects, force sensor-less power assist control (FSPAC) aims to estimate the force to assist by using only encoders. However, FSPAC is generally not robust against plant uncertainties. In this paper, FSPAC with variable gain is proposed and implemented on a system representing a door, actuated by a linear motor. The results show that the proposed control design increases FSPAC’s safety and robustness.

I. INTRODUCTION
Recently life expectancy and aging population are increasing in many countries. Therefore power assist devices as electro-mechanic wearable suits and wheelchairs are expected to be always more important. For these devices new hardware and control design approaches are being investigated. Differently from typical industrial robotic applications, power assist device deeply interact with human being. This new approach in robot and control design have been often referred as “human-friendly motion control” [1], [2].

The user’s force applied on the device must be known in order to assist the user itself. The user force is often measured using force sensors, which have several disadvantages. Force sensors are usually noisy, heavy, and can measure the force only if it is applied on the sensor itself. Moreover, force sensors present measurement delay, which can have significant impact on power assist devices performances.

To overcome these disadvantages, in other researches [3], [4] [5], the force to assist is not measured by force sensors, but it is estimated by using simple encoders. The force estimation is realized by using force observer design, which is based on disturbances observer. Using this control design the devices are lighter, the force can be applied on any point of the device, there is no measurement delay. However the main problem of Force Sensor-Less Power Assist Control (FSPAC) is that the precise plant dynamics and friction models are needed. To cope with this aspect, approaches as learning process [6] or model independent force observer [7] have been proposed.

In this paper we propose FSPAC design that uses a variable gain (VG) to increase robustness and safety of power assist devices. The proposed control design was successfully implemented on a system composed of a door and actuated by a linear motor.

At first, the general FSPAC structure is described (Sec. II-A) together with the proposed FSPAC with VG (Sec. II-B). Then the experimental apparatus and system modelling are illustrated (Sec. III). In Sec. IV the experimental results of the effect of a VG on FSPAC is analyzed. Finally the conclusion are described (Sec. V).

II. FORCE SENSOR-LESS POWER ASSIST CONTROL DESIGN

In this section the general structure of Force Sensor-Less Power Assist Control (FSPAC) [8] is illustrated at first (Section II-A). After that, the proposed novel control approach with variable gain (VG) is described (Section II-B).

A. General Structure of Force Sensor-Less Power Assist Control

In Fig. 1 the general structure of FSPAC is shown.

The real plant dynamics are represented by \( \frac{1}{Js + B} \) where \( J \) and \( B \) are the inertia and the damping factor, respectively. The output is the actual velocity \( (v_a) \). This shows how FSPAC is different from force control. In force control the aim of the controller is to track the force value. On the other hand, in FSPAC states such as position or velocity are to be controlled. The controller is made of four main parts highlighted in Fig. 1: the disturbance observer, the force observer, the model impedance, and the feedback gain:

- The disturbance observer includes the inverted plant dynamics model, \( \left( \frac{J_s + B}{T_s + 1} \right) \) where \( J_s \) and \( B_s \) are respectively the nominal inertia and damping factor, a low pass filter \( \left( \frac{1}{T_0 + 1} \right) \), and its feedback gain (DistG). It is used to reject all the disturbances so that the real plant dynamics are as close as possible to the nominal model ones.
- The force observer includes the inverted plant dynamics model, \( \left( \frac{J_s + B_s}{T_s + 1} \right) \) and a low pass filter \( \left( \frac{1}{T_1 + 1} \right) \). It is actually a disturbance observer with the aim to estimate the force to assist. It can also be integrated within the disturbance observer. That’s the case in which \( T_0 \) is set to be the same as \( T_1 \).
• The model impedance represents desired mechanical impedance of the controlled system. It is used to determine the model velocity \(v_m\), that is the desired velocity response of the controlled system. In order to assist (instead of reject) the disturbance estimated from the force observer, the impedance model is designed so that \(B_M < B_n\) and \(J_M < J_n\).
• The feedback gain is designed so that actual velocity \(v_a\) tracks the model velocity \(v_m\). A PID controller is generally used.

There are three signal paths through the real plant:
1) The external (human) force which acts directly on the plant.
2) The positive feedback loop through the model impedance and the feedback gain which aims to assist the user.
3) The negative feedback loop through the disturbance observer and its gain (DistG) used to reject disturbances.

The reference force/torque (\(RefF/T\)) sent to the plant from the controller is given by the last two paths:

\[
RefF/T = (v_m - v_a) \ast PID - disturbance \ast DistG
\]  

(1)

where PID is the gain value of the positive feedback loop (Fig. 1). Disturbance and DistG are the disturbance observer output and feedback gain values, respectively.

**B. Design of FSPAC with Variable Gain**

The structure of the proposed FSPAC with VG is shown in Fig. 2.

In the proposed structure one disturbance observer is used both to reject the disturbances and to determine the force to assist. The main difference with feedback-oriented force control shown in Fig. 1 is the design of the feedback gain. Instead of the traditional PID controller, the feedback gain value in the proposed control varies in respect to the value of the actual velocity \(v_a\).

Before describing in detail the design of the VG, it is opportune to consider how the reference torque (\(RefF/T\)) is given to the motor by the controller. From the block diagram in Fig. 2:

\[
RefF/T = (v_m - v_a) \ast VG - disturbance \ast DistG
\]  

(2)

Where VG is the variable gain value which depends on the absolute value of the actual velocity (\(|v_a|\)) in the way illustrated in Fig. 3.
In the x-axis of Fig. 3 there is the absolute value of the actual velocity while on the y-axis there is the value of the VG.

The VG model involves 4 parameters ($V_{G\text{max}}$, $v_1$, $v_2$, and $v_3$). These parameters are related to disturbance rejection, to how the user feels the device, as well to factors as friction and inertia as described in the following:

- $V_{G\text{max}}$: can be referred as the maximum assistance. This parameter is to be chosen as large as possible in order to highly assist the user at low velocity but not too large so to keep maximum velocity/acceleration under a certain value.
- $v_1$: disturbance rejection velocity. For $0 \leq |v_1| < v_2$ the value of the VG is set to 0. This creates a sort of dead zone in which the estimated force/torque and disturbance are not assisted. This is useful as the VG helps the disturbance observer to reject all disturbances, especially the high frequency ones that are not to be assisted when the velocity is almost 0 ($v_1$ should be very small).
- $v_2$: velocity of maximum assistance. This parameter has impact on how the user feels the device. A too high value will generate a slow rise of the assisting force/torque and therefore low assistance at low velocity with the consequent that the user will feel constrained. A too high value of $v_2$ will also generate too high assistance for higher velocity. $v_2$ is a velocity in which the friction is high (i.e. during the passage from static to dynamic friction) and the device inertia is to be won by the user.
- $v_3$: maximum allowed velocity. This parameter has an influence on how the user feels the device. A low value would let the user feel constrained while a too high one will generate too much assistance and dangerous high velocity/acceleration. When the velocity is higher than $v_3$, the friction is in the dynamic region and the initial device inertia is already won by the user.

III. EXPERIMENTAL APPARATUS AND SYSTEM MODEL

The proposed control method was implemented on the system shown in Fig. 4.

The system has one degree of freedom. It is composed of a door — the wooden bar on which bricks are placed — actuated by a linear motor through a link. The only sensor used is a linear encoder along the motor axis. Further experimental apparatus characteristics are shown in Tab. I.

The system is modelled as in Fig. 5.

The dashed (brown) lines represent the wooden bar of the door which can rotate around the z axis. On the system there are 2 main input forces — one is the external force applied by the user, and the other is the force applied by the linear motor on the end of link 2 that is $F$ in Fig 5. In order to estimate the external force, the value of the nominal inertia ($I_n$) in the inverted plant dynamics model ($\frac{l_1+l_2}{l_1}$) is considered constant in respect to the z axis around which the door rotates. The torque applied around the z axis caused by the force $F$ is $T_1$ and is determined from the Jacobian of the system as follows:

$$J = \begin{bmatrix} -l_1\sin(\theta_1) - l_2\sin(\theta_1 + \theta_2) & l_2\sin(\theta_1 + \theta_2) \\ l_1\cos(\theta_1) + l_2\cos(\theta_1 + \theta_2) & l_2\cos(\theta_1 + \theta_2) \end{bmatrix}$$

where $\theta_2$ is negative.

As the linear motor applies a force only along the x axis $F_x = F$ and $F_y = 0$. Therefore:

$$T = J^T F$$

$$= \begin{bmatrix} -l_1S_1 - l_2S_{12} & l_1C_1 + l_2C_{12} \\ l_2S_{12} & l_2C_{12} \end{bmatrix} \begin{bmatrix} F \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} -l_1S_1 - l_2S_{12}F \\ -l_2S_{12}F \end{bmatrix}$$

where $S_1 = \sin(\theta_1)$, $C_1 = \cos(\theta_1)$, $S_{12} = \sin(\theta_1 + \theta_2)$ and $C_{12} = \cos(\theta_1 + \theta_2)$.

Tab. II shows the values of the parameter used in the VG design.

Tab. III shows the values of the parameter used in the controller design.
### TABLE II

**VG PARAMETERS’ VALUES**

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>$V_{G\text{max}}$</td>
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<td>rad/s</td>
</tr>
<tr>
<td>$v_1$</td>
<td>0.005</td>
<td>rad/s</td>
</tr>
<tr>
<td>$v_2$</td>
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<td>rad/s</td>
</tr>
<tr>
<td>$v_3$</td>
<td>1.2</td>
<td>rad/s</td>
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</table>

### TABLE III

**CONTROLLER PARAMETERS’ VALUES**

<table>
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<th>Unit</th>
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</thead>
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<td>kgm²</td>
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<td>$B_n$</td>
<td>4.4</td>
<td>Nms</td>
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<td>$J_m$</td>
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<td>kgm²</td>
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<td>$B_m$</td>
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<td>$T$</td>
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<tr>
<td>DistG</td>
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<tr>
<td>P gain</td>
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</tr>
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</table>

### IV. RESULTS

In order to show validity of the proposed control method the response of the system using FSPAC with constant gain (Fig. 1) and the proposed one with variable gain (Fig. 2) is compared. Two types of experiments were carried on:

1) **User input**: the user pushes or pulls on a side of the door. The door is considered to be opening when the user pushes and closing when pulls. This is to show what would be the typical response of the system during opening-closing cycles under a user input force.

2) **Constant-force input**: a weight of 1.5 kg was connected to the tip of the door by a wire and a pulley as shown in figure 6. The door was held in position 1 ($\theta_1 = 67\,\text{deg}$), then it was left free to move under the weight force till it reached the position 2 ($\theta_1 = 52\,\text{deg}$), that is when the weight reached its home limit. Therefore the force applied by the weight on the door can be considered constant in module, but not in direction respect to the door’s end. The purpose of this experiment is to compare FSPAC with constant gain and FSPAC with variable gain to the same input (filtering any possible influence of the user).

The results of two type of experiments are shown in section IV-A and IV-B, respectively.

#### A. User input

In Fig. 7 the results for FSPAC with both constant gain (Fig 7(a)) and VG (Fig. 7(b)) are shown for a direct comparison. The value of the constant gain is 0.6 while the ones of the VG are shown in Tab III.

In both cases the user pushes on the door 3 times and pulls 2 times. The data shown in Fig. 7 are the angular velocity of the door ($\dot{\theta}_1$), $T_1$ — calculated from the reference input to the linear motor as if the system efficiency was 100% —, the estimated disturbance from the disturbance observer around the z axis, the model velocity ($\dot{v}_m$), and the value of the variable gain — only for Fig. 7(b) where the value of the variable gain is in respect to the left y axis.

There are 2 main problems in the case of FSPAC with constant gain:

1) When the door is accelerating, as for example around second 1 in Fig. 7(a), the generated torque is too high therefore the door is opening too fast and loses contact with the user.

2) When on the door is coming to stop, as for example between seconds 1.5 and 2.5 in Fig. 7(a), friction non lineairities cause an oscillatory reference disturbance, followed by oscillatory torque which can bring to oscillatory velocity.

A lower constant gain could only attenuate the problems described above, but the assistance would be too small, especially at low velocity.

As shown by the results in Fig. 7(b) the previous two problems are overcome by the variable gain.

When the user start pushing (or pulling) the door the VG rapidly increases so to help the use to win the door inertia, then the assisting torque gradually decrease, so that the user does not lose contact with the door. Therefore the assistance is provided in a smooth way.

When on the door is coming to stop the VG goes rapidly to 0, avoiding oscillatory torque reference, and therefore oscillatory velocities.

#### B. Constant-force input

In Fig. 8 the results for FSPAC with constant gain and a constant-force input are shown. The constant gain is set to 0.6.

In Fig. 9 the results for FSPAC with variable gain and constant-force input are shown.

These results confirm that by using the VG (Fig. 9) the torque reference rises faster and is not oscillatory when the door is coming to stop. Moreover high torque reference, leading to possible dangerous velocity, is avoided.

### V. CONCLUSIONS

Power assist devices such as wearable suits and wheelchairs are becoming more and more important due to the always more aging society. Such devices require a new approach in both hardware and control design which can be referred as “human-friendly motion control”.

In traditional approach force sensors are used to measure the force applied by the user on the device. In order to
overcome the disadvantages of force sensors such as high cost, high weight and measurement delay, Force Sensor-Less Power Assist Control (FSPAC) have been proposed in many researches. It is based on disturbance observer technology to determine the force to assist, as a consequence the only needed
sensors are encoders. The main problem of FSPAC is the robustness against real plant uncertainties.

In order to cope with this problem FSPAC with variable gain is proposed. The variable gain model is based on parameters related to friction and inertia, as well as to disturbance rejection and to the way the user feels the device.

The proposed control design was implemented on a low friction system representing a door, actuated by a linear motor. Experimental results show that the proposed FSPAC with variable gain can increase safety and robustness. Compared to traditional force sensor-less power assist control, FSPAC with variable gain can assist more smoothly the input human force during opening and closing phases. Moreover high and dangerous velocity is avoided.

REFERENCES


