Sensorless position/force control of electromagnetic linear actuator

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Abstract
Sensorless control means for a gripper based on a solenoid actuator are discussed in order to reduce the number of components in an autonomous mobile robot. As the information of the armature position is found in the solenoid’s impedance, a method based on the current difference between start and end of a pulse width modulated impulse is introduced and evaluated by experiments. The controller is implemented in three phases, starting with the closing of the gripper in position control, the transportation phase with a fixed retention force in force control and ending in the opening phase of the gripper.

1 Introduction
Autonomous mobile robots require a high integration of sensors and actuators. The number of components can be significantly decreased, when the integrated actuators act as well as sensors. Cost-efficient solenoid actuators provide in their impedance the information of the armature position. With a proper analysis method, the information can be evaluated during operation. Together with the knowledge of the non-linear force/position characteristic of the solenoid, a combined position and force control can be realised without the need of additional sensors. The proposed method is suitable for a gripper, which typically implements a combined position/force control [1].

2 Sensorless position estimation

2.1 Physical principles
The information of the armature position is found in the impedance of the driving coils. The actuator’s impedance \( Z(x) \) as a function of the position \( x \) is described as \( Z(x)=R(x)+j\omega L(x) \). Two different physical principles have an effect on the impedance [2]: the variable reluctance and the eddy current density. The reluctance of the armature core, that has a higher permeability than the air in the gap, is lower than the reluctance of the air gap. Thus reducing the air gap, the total reluctance will decrease, providing a higher inductance \( L \) of the coil.

When we define the position \( x \) starting with the armature fully immerged in the coil (compare figure 1), the inductance will decrease with an increasing \( x \). When conducting material approaches the time variant magnetic field of a coil, eddy currents are induced in the conducting material. These eddy currents create a magnetic field which acts contrary to the exciting field. Thus, the flux lines of the exciting magnetic field will be displaced, which results in a decreasing inductance \( L \). This effect acts in contrary to the effect of the variable reluctance. Both effects consider the inductance of the coil. The eddy currents have an additional effect on the real part of the coil’s impedance: The armature of the coil can be seen as a secondary winding of a transformer with a high load conductance given by the resistivity and the diameter of the core [3]. When the armature immerses into the coil, the mutual inductance of the transformer increases which results in higher currents and a higher loss in the core. Thus the real part of the coil’s impedance – expressed in the equivalent electric circuit by \( R \) – will increase.

2.2 Impedance analysis in sensorless systems
The key of sensorless control is the impedance analysis during operation. Typical measurement circuits for eddy current sensor evaluation such as relaxation oscillators [2] or bridge circuits [5] can not be used. In [6] the impedance of the coil is calculated by short positive and negative voltage impulses and the current response. This method is not suitable for sensorless actuator operation. Typically a solenoid is controlled by a pulse width modulated (PWM) power supply. Especially for PWM controlled actuators, Rahman presents in his work the
differential current measurement [7], which allows a position control of 50% of the total stroke. Adapted from this method, we measure the current of the solenoid at the beginning and at the end of each PWM impulse. Thus, the current in the coil rises according to (1) during the active PWM impulse with a time constant \( \tau = L/R \). As the inductance \( L \) and the resistance \( R \) both depend on the armature position due to the eddy current effect and the variable reluctance, the time constant \( \tau \) is directly linked to the armature position \( x \).

To model the actuator, an equivalent circuit diagram is used, which implements the solenoid as in figure 1 with an additional shunt resistance \( R_S \) in series and an ideal recovery diode in parallel. The measured response of the voltage at the shunt resistor is shown in figure 2.

\[
\Delta u_S = \begin{cases} \frac{U_1 - U_2}{R_S} & 0 \leq t < t_{pw} \\ 0 & t_{pw} \leq t < T \end{cases}
\]

where \( U_1 \) and \( U_2 \) correspond to the difference voltage at the shunt resistor in the case of the selected actuator.

The model of the actuator can be described with a first order differential equation as in (1).

\[
L \cdot \frac{dx}{dt} + (R + R_s) \cdot \frac{dx}{dt} = U(t) \text{ with } U(t) = \begin{cases} U, & 0 \leq t < t_{pw} \\ 0, & t_{pw} \leq t < T \end{cases}
\]

Solving the differential equation (1) for a single PWM period \( T \) with the active PWM impulse in \( 0 < t < t_{pw} \) for the voltage at the shunt resistor \( R_S \), we obtain (2)

\[
u_s(t) = \begin{cases} R_s \cdot \frac{U}{(R + R_s)} \left(1 - e^{-\frac{t}{\tau}}\right) & 0 \leq t \leq t_{pw} \\ u_s(t_{pw}) \cdot e^{-\frac{t - t_{pw}}{\tau}} & t_{pw} \leq t < T \end{cases}
\]

\[
\tau = \frac{L(t_{pw} \cdot x)}{R(x) + R_S}
\]

with \( \tau(x) = \frac{L}{R(x) + R_S} \) (3) where \( \tau \) is the time constant depending on the shunt resistance \( R_S \) and on the impedance of the coil. The inductance \( L \) and the resistance \( R \) of the coil both depend on the position \( x \), whereas \( L \) in addition depends on the current in the coil, which is proportional to the applied pulse width \( t_{pw} \). If we assume that the changes of the inductance \( \Delta L \) due to current and position are small compared to the changes of real part of the coil’s impedance expressed by \( \Delta R \) (4), we obtain a simplified model for the difference voltage \( \Delta u \) (5), see figure 3:

\[
\begin{align*}
\frac{\Delta L(t_{pw} \cdot x)}{L} & \ll \frac{\Delta R(x)}{R} \\
\Delta u_s(x,t_{pw}) & = \frac{R_s}{R(x) + R_S} \left(1 - e^{-\frac{t_{pw}}{\tau}}\right) \left(1 - e^{-\frac{(T - t_{pw})}{\tau}}\right) \\
\text{with} & \quad \tau(x) = \frac{L}{R(x) + R_S}
\end{align*}
\]

Experiments with industrial solenoid actuators have shown a nearly linear course of \( R \) depending on the armature position \( x \). The knowledge of two values for the corresponding resistance \( R_{x_1}, R_{x_2} \) at two different positions \( x_1, x_2 \) is sufficient to feed the mathematical model according to equitation (5). Figure 3 shows the results of the simulations based on (5) and the measured values of the voltage difference \( \Delta u_s \) at the shunt resistor \( R_S \).

As we learn from (5), the proposed method does not work for tiny and very wide pulse widths, because the current has not enough time either to rise in the active period or to fall in the inactive period, which results in a current difference reaching zero. The method works fine for pulse widths in the range of 20 to 80 percent in which the relative difference between model and the measured data is less than 4 percent. Thus the simplification of (3) has lead to no significant error for the difference voltage \( \Delta u_s \) in the case of the selected actuator.

![Figure 2](image)

**Figure 2.** Voltage response at shunt resistor during PWM period

![Figure 3](image)

**Figure 3.** Simulated and measured values of the voltage difference \( \Delta u_s \) according to (5)
The PWM frequency plays a significant role in the proposed method. The eddy currents depend on the exciting frequency: simulations of a solenoid have shown the frequency sensitivity of eddy currents with a maximum at 50 Hz [4]. In addition, the PWM frequency needs to be properly selected to allow an evaluation of the time constant $\tau$ during the on or off phase of the PWM signal. In the experiments the PWM time period $T$ is about 4.5 times the average time constant $\tau$.

Assuming that the PWM frequency is high compared to the velocity of the armature, any induced voltage due to the armature’s movement is eliminated because of the differential principle.

### 3 Position and force control

#### 3.1 Dynamical Model

The electromagnetic force $F$ of the actuator depends on the armature position $x$ and the average current $i$ in the coil. Thus the proportional dependency can be written for the linear range of the current as in (6):

$$F \sim \frac{i}{x^2} \tag{6}$$

![Figure 4. Measured relative force against position $x$ and pulse width $t_{pw}/T$](image)

The average current is directly proportional to the pulse width. The electromagnetic force $F$ versus armature position $x$ and pulse width $t_{pw}/T$ is measured with a force sensor and a linear stage. The results are shown in figure 4. The actuator is arranged together with a return spring (compare figure 1). The dynamic model of the actuator is shown in equation (7):

$$m\ddot{x} = F(x, t_{pw}) - K_s x - F_L \tag{7}$$

where $m$ is the mass of the armature and attached mechanics, $K_s$ is the spring constant, $F_L$ is the load force, which may include the gravitational force and $F$ is the electromagnetic force of the solenoid [7]. Frictional forces will be neglected and the spring constant is considered as linear. In case of an horizontal arrangement, the load force $F_L$ is equivalent to the force that the armature can apply to an object. In position control $F_L$ will become zero. In force control $F_L$ will express the applied force.

#### 3.2 Position control

The process of gripping works in three phases. In the first phase, position control with a low velocity is used to close the gripper.

The position control is independent from equation (7), as equation (5) allows an estimation of the position independent of external forces: With the given characteristics shown in figure 3, the position can be derived from the voltage difference $\Delta u_s$ and the given pulse width. In section 2 we have described a quasi static scenario for one PWM impulse, but now we have to deal with a dynamic scenario, as the position control will force fast changes of the pulse width together with a real time position estimation. It is obvious, that a change of the pulse width will result in a transient characteristic of the current change. Thus, with changing the pulse width, we can not expect to get the expected difference voltage $\Delta u_s$ according to (5) with the consecutive PWM impulse. For this reason, we average the voltage difference $\Delta u_s$ over a period of consecutive impulses with an identical pulse width. This has an effect on the control response time and may compromise the stability of the controller. In the case of our experiment, the force sensor has a long response time and therefore determines the overall control response time.

#### 3.3 Force control

When the gripper touches an object, the armature position gets fixed. Assuming a fixed position $x$ means eliminating the term $m\dot{x}$ from (7) which gives equation (8):

$$F_L = F(x, t_{pw}) - K_s x \tag{8}$$

Therefore $F_L$ can be estimated on the basis of the current position $x$ and the characteristics of the actuator force $F(x, t_{pw})$. When $x$ is fixed, $F_L$ will rise together with the position error. The control system can assume contact with the object and switch into the second phase. According to (8) and the force characteristics $F(x, t_{pw})$ in figure 4, a fixed retention force can be applied to the object in order to transport the object.
In force control, the proportional dependency of the force on the current – respective pulse width – is used as basis. Thus force control is reduced in providing a fixed average current by applying a fixed pulse width. This forces a quantisation of possible retention forces, in steps of available pulse widths. The advantage of a fixed pulse width is, that the position estimation can now work without dynamic changes of the pulse width. When starting the transportation, the inertia of the load mass may have an effect on the gripper: the gripper position \( x \) may change. In force control, the position is monitored and any changes will automatically result in adjusting the applied pulse width due to the dependency of the actuator force on the position.

In phase three the pulse width of the actuator is reduced to a minimum. The opening of the gripper can be monitored by evaluation of the gripper position. In case the gripper clings to the object or the gripper can not open properly for any other reason, the controller can detected the failure on basis of the position estimation.

### 3.4 Experimental results

Figure 5 shows the experimental set-up. Instead of a real object, the solenoid directly applies its force to the force sensor. The return spring is mounted inside the solenoid.

![Figure 5. Experimental set-up](image)

Figure 6 and 7 show the process of gripping with the proposed methods. A trajectory for the position control is given, that defines the process of closing the gripper. After \( t \approx 10 \) s, the magnetic force gets too high, which leads to a fast closing of the gripper.

The position control detects, that the evaluated position \( x \) shown in figure 6 does not change any more at \( x \approx 8 \) mm. Thus, the controller gets into the second stage. This process can be seen in figure 7: the measured load force \( F_L \) at the object rises with the first contact (peak at \( t \approx 10 \) s). The position controller immediately reduces the applied force due to the evaluated position error, but soon the object-contact is realised and the system switches into force control. The applied retention force is now evaluated with equitation (8) and monitored (compare figure 7). The opening of the gripper is monitored and can be seen again in figure 6.

![Figure 6. Target trajectory and evaluated position of the gripper](image)

![Figure 7. Measured and evaluated retention force at the object](image)

The position controller is implemented by a PI-controller. Due to the required measurement time for the force sensor, the control response time has to be long. This inhibits a fast reaction of the position controller and compromises the stability of the controller. When operated without force sensor, the control response time is only limited by the averaging of the difference voltage measurement for consecutive PWM impulses. Further experiments without force sensor have shown, that the controller is able to operate the actuator nearly over the whole stroke. The usage of a non-linear controller as described in [8] may further improve this. Regarding the dynamics of the set-up it depends like the stability of the control loop in the same manner on the long measurement period of the force sensor. Without the sensor, a much higher dynamic of the actuator can be achieved.

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3.5 Implementation

Experiments with a set of solenoid actuators have shown, that the simplification of (3) can not be made in general. A rise of the inductance for small $x$ (especially, with a wide pulse width) provides a characteristics that flattens or even arises again (instead of the monotone falling as in figure 3), when reaching $x=0$. This results in an ambiguous characteristics, not suitable for sensorless control based on the proposed method only. To eliminate the ambiguity the method needs to be combined with a dynamic model of the actuator or the actuator design needs to be optimised.

For a further development, we want to characterise the actuator design with the finite element method in order to optimise the actuator for sensorless control. Another aspect of the actuator design is the influence of the close vicinity of the actuator with regard to conductive or ferromagnetic materials on the impedance of the actuator. Temperature influence on the inductivity and the measurement principle need to be analysed, before the system can work effectively outside the laboratory environment [9].

Although we neglected friction in the dynamical model as described in equation (7), it has to be considered. In the experiment set-up we assume an ideal model, with the object at the fixed gripper’s hand. As in the real world, the object may be placed anywhere between the two hands of the gripper, the force to move the object in the proper position may be higher than the required retention force: the procedure as described above will fail, as it will apply a retention force and start the transportation process, although the object is not ready in place. A solution with two moveable parts of the gripper, both controlled by the proposed algorithm would allow the gripper to clamp the object properly.

4 Conclusion

On the basis of a cost-efficient solenoid actuator a sensorless method for position and force control is presented. The method – based on the measurement of the current difference between on and off phase of PWM supply – is evaluated with experiments regarding the performance of a gripper.

The sensitivity and the measurement uncertainty of the position estimation depends on the actuator (core materials, geometry, inductance, conductivity, etc.), on the PWM-frequency and on the enclosure and close environment of the actuator. Ferromagnetic and conducting materials in the vicinity change the sensor characteristics of the actuator. For stationary systems with a stationary environment, an on-site calibration can eliminate these side effects. In an open environment, as well as in the case of a gripper, these side effects needs to be eliminated by a proper design of the actuator. A further analysis based on the finite element method shall define parameters to optimise the sensorless principle for electromagnetic linear actuators.

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6 References