Design, tuning and evaluation of a stand-alone nitinol based thermomechanical actuator driver with a closed-loop position control system

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Abstract. Nitinol based actuators can be used in many applications. Many of them are simple logic-type applications where intermediate positions or contractions are not required. For such applications, a simple current limiting circuit with enable function can be used. The biggest problem is when we want to use the actuator for positioning applications. In this case, by simply adjusting the current flowing through the nitinol wire is not going to solve the problem. On one hand, the range where we can adjust the current is very small. On the other hand, the hysteresis and thermal inertia are involved in the process. The last and the worst thing is the ambient temperature that will vary in a random way. As a conclusion, the author’s original research for a dedicated driver with position feedback did the job done, eliminating all the related problems. Finally, the driver was implemented, tuned for the mechanical test jig and evaluated under rough conditions in order to prove that the driver can reject the external disturbances. Furthermore, unlike a traditional on/off driver, the designed driver can prolong the lifetime of the actuator by keeping the actuator current at a safe level even in saturation conditions and, by limiting the maximum rate of change of the temperature, thermal shocks can be avoided.

1. Introduction

Open loop control is not good enough to meet the desired performance from a nitinol wire based actuator. Even when the current is set and maintained to a certain value in order to get a certain temperature and contraction of the nitinol wire, it is not enough to keep the contraction at the same value. The airflow around the wire and the changes in the ambient temperature will alter the temperature of the nitinol wire, altering the contraction level. The driver designed to for the nitinol actuator is able to automatically modulate the drive current in such a way that the temperature will remain nearly constant even when the actuator is exposed to an airflow with random intensity and temperature. The driver is not doing that by measuring and correcting the temperature of the actuator, simply because the position feed-back is used. Another important fact is the contribution of the mechanical system. The friction, stick-slip and compliance will also compromise the accuracy and repeatability of the positioning system. To achieve optimum performance, a cascaded control system is used. The inner loop is modulating and regulating the current flowing through the actuator and the outer loop is designed for position control. The output signal from the position regulator becomes the reference signal for the current regulator. In this configuration, the inner loop response time must be at
least three times faster than the external one. This is a basic control theory statement. In this case, the inner loop response time is at least two orders of magnitude lower than the outer loop. Because of this reason, the control system stability is not compromised. Previous research was done by Song to successfully design and control a rotary servo device using sliding-mode based robust control approach [1]. Another previous research was done by Asua et al. on a neural network to compensate the hysteretic behaviour of the nitinol wire [2].

2. Methods
Because of the successful experience in the field of control systems for various applications, the first decision was to use just a high gain proportional controller. It worked nearly fine but the system was not in a stable state. Hariri et al. stated that a proportional controller alone is insufficient to obtain stabilized control responses when the nitinol wire is subjected to dynamic loading [3]. So, it was mandatory to solve the problem in a simple yet, reliable, and low-cost way. Based on experience, the decision was to design and insert a phase-advance circuit in the feed-back path of the external loop (position loop). Inserting the circuit was efficient and a fast way to solve the problem. The tuning was the only thing that was required. A multi-turn potentiometer, was used in a phase shift circuit to precisely adjust the phase advance factor until the oscillation of the system stopped. Parallel with the practical circuit, computer simulations were performed using the demonstration version of the Proteus software from Labcenter Electronics. With the help of this software, it was possible to do mixed mode simulation, combining Laplace transform based simulation with electronic circuits on the same page. For this case, displacement was converted to voltage in order to close the loop. The simulation scheme was simplified a lot. Since the research was only for a nitinol actuator driver, the actuator was simply modeled as a first order low-pass filter to simulate the delay time needed for the actuator to heat-up and the mechanical displacement multiplier was modeled using a Laplace equivalent block of a second order low-pass filter to simulate not only the delay time but also the mechanical inertia and damping factor.

Figure 1. Block diagram.
Even if some parameters were empirically chosen for the mechanical part, in the end, the dynamic response of the simulated system was close to the real mechanical jig’s dynamic response. The holistic overview of the system is featuring the control system, mechanical part and finally the two sensors that are used for measuring and closing booth loops. Everything is starting with the position reference signal that can be a constant DC voltage, a signal from a potentiometer and finally, a signal coming from a digital to analog converter. Figure 1 is featuring all the components in order to fully understand the entire system.

Referring to the Figure 1, a position setpoint constant block was used. The first order low-pass filter is used for two purposes. The first one is noise filtering. This is required when noisy signal sources are used or pulse width modulation (PWM) signal’s duty cycle must be converted into an average DC signal. The second purpose is to limit the actuator’s temperature rate-of-change (to avoid thermal shocks). The position reference signal (rp) becomes a filtered position reference signal (rpf). The difference between the filtered position reference signal and phase advanced measured position signal represents the position error signal (εp). Because the value of the error signal is relatively low, the error signal must be multiplied by a proportional constant. Due to the fact that general purpose operational amplifiers are used in open-loop mode, a proportional constant of 100000 is easy to achieve because it is a typical open-loop gain of the operational amplifier used for practical testing. The fact is that even a very small error will saturate the amplifier (in this case, the saturation level is 7V). In a practical filtered derivative proportional-integral-derivative (PIDF) controller, such a high gain is not acceptable due to the fact that the system will not be stable. In this system, the phase-advance circuit is keeping the system in a marginally stable state even with such a high gain. Once the amplified error signal is obtained, a divider is used. The purpose of this divider is to limit the peak current that is allowed to flow through the nitinol wire. Without the divider, the nitinol wire will become a slow-blow fuse. For this application, the maximum current was limited to 0.3A. By adjusting the division ratio, the system can be tuned for different actuators with different characteristics. For example, if two identical actuators are parallel connected, the division ratio can be changed accordingly and if two identical actuators are series connected, the user is not prompted to change the division ratio because the current will be the same, thanks to the inner loop. The divided error signal (rcd) becomes the current reference for the current-mode controller (inner loop). In this case, the same thing happens. The current error signal (εc) is multiplied by a factor of 100000 and is sent to the PWM power stage that is converting the signal level into a corresponding duty cycle which is no longer a continuous signal. Because of that, a first order low-pass filter is used. So, the absolute current flowing through the actuator is not constant but the mean value is approximately constant. In practice, an inductor is used to store the energy and work in a continuous mode operation (the inductor current never falls to zero). Thanks to the local storage element (the inductor), current ripple is very small (approximately 25 mA). Because of the high switching frequency (>38 kHz) and the thermal inertia of the nitinol wire, the effect of this ripple is negligible. For the inner loop controller, the filtered current feedback signal (fcf) is closing the loop in order to regulate the drive current for the actuator. In the practical approach, a 1Ω current shunt resistor and RC low-pass filter are used. In this case, the circuit will give 1V/1A. Basically, the entire circuit will be a switching-mode 1A/V transconductance amplifier to drive the actuator in an energy-efficient way. The actuator will behave in this case like a current to displacement converter where the input is the nearly the root-mean-square (RMS) current (yc) and the output is the displacement (Δxa). In the end, a displacement multiplier is used, since the nitinol wire is only contracting approximately 5% of its total length at maximum current. The practical multiplier is using a lever mechanism and a ball-bearing is used to minimize the friction. Using a sensor, the multiplied displacement (Δx dm) is converted to voltage (fp) which is sent to the phase advance block in order to obtain the final signal (fp p-a) and close the outer loop. Two types of sensors were used. The first one was a capacitive proximity sensor and the last one was a Hall effect proximity sensor. Due to the fact that the homemade capacitive sensor was not good enough, the Hall effect sensor was used in the end. Both sensors require signal-conditioning circuits but the last one only require a constant current supply and a differential amplifier with gain. The final result was
very effective (from a displacement of only few millimeters, a voltage range between 0.5V to 6V full scale was obtained). The tuning of the sensor was mechanically done. The sensor required precision placement and in order to linearize the response, it was placed at a slight angle (not parallel to the permanent magnet). Even one millimeter error is enough to create problems. In order to enhance the precision, the permanent magnet was glued to the end part of the multiplier and not to the actuator. In order to get closer into the system, Figure 2 illustrates the simulation of the control system.

Figure 2: Simulation of the control system.

Unlike the first block diagram, the simulation block diagram is simpler to understand, it shows the real parameters used in the simulation and the mathematical formulas inside the functional blocks. In other words, nothing is hidden from the reader. Every parameter is shown, so the reader can replicate the simulation in order to review the stated dynamic behaviour of the system. It is good to be stated that the mathematical model was simplified in a manner that will reduce simulation time, complexity of the diagram and in the same time, it will simulate the behaviour pretty well. The error amplifiers were modelled with saturation and the saturation values are the real practical ones. For the position error amplifier the positive saturation value is 7V and negative saturation is zero volts. This is because the operational amplifier is powered from a regulated eight volts power supply and the amplifier is not rail-to-rail output type. For the current error amplifier, the positive saturation value is 12V and negative saturation is zero volts. This is because the power amplifier is powered from a regulated 12 volts single power supply. In this simulation, the signal conditioning circuits for sensors were not included, the power circuit was modelled using the same error amplifier functional block. The arbitrary current controlled voltage source is modelling the nitinol wire actuator current-to-displacement conversion and the first order low-pass filter is modelling the thermal inertia of the actuator. The cut-off frequency is 0.8 Hz in order to create a delay time that is near the delay time...
required for warm-up of the nitinol wire actuator. In this simulation, a voltage range of 0.1V means one millimeter displacement and a voltage range of 1V means a displacement of ten millimeters. So, for a current of 250mA through the arbitrary current controlled voltage source, a displacement of 2.5 millimeters is obtained. The simplified displacement multiplier (LP5) is modelled using a second order low-pass filter with a static gain of 20 to simulate the displacement multiplication. The damping value and the normal frequency were empirically chosen until the dynamic response was similar to the test jig’s response. To test the system, a step signal was applied to the input. The step signal was generated using a pulse generator where the initial value was set to zero and the pulsed (high) value was set to 4V, corresponding to a displacement of 40mm. Later, on the final simulation diagram, another type of generator was used to generate a pattern of steps with both positive and negative going edges. After the step response was evaluated, a sinusoidal waveform generator was used in order to show that the system can follow the reference signal. Step response was evaluated using the oscilloscope in order to confirm the simulated dynamic response. As can be seen in the Figure 2, the electrical resistance of the nitinol wire was also included. After the resistance of the nitinol wire was measured, a 4Ω value was inserted. Even if the inner loop is able to keep a constant current through the nitinol wire, it is a maximum limit where the current will no longer be at the desired level. This limitation is related to the supply voltage of the transconductance amplifier. For example, in this case, the maximum current can be calculated using the formula (1).

\[ Im = \frac{Ups}{(RdsON + Ri + Rw + Ra + Rs)} \]  

where \( Im \) is the maximum current; \( Ups \) is the power supply voltage; \( RdsON \) is the saturation resistance between the drain and the source of the power MOSFET used in the test circuit; \( Ri \) is the equivalent series resistance of the inductor used in the circuit; \( Rw \) is the resistance of the wires connecting the actuator to the transconductance amplifier; \( Ra \) is the nitinol wire actuator’s resistance and \( Rs \) is the resistance of the current shunt resistor. For this application, the rated values are: \( Ups=12V; RdsON=0.06\Omega; Ri=0.2\Omega; Rw=0.2\Omega; Ra=4\Omega \) and \( Rs=1\Omega \). With these values, the maximum current will be around 2.2A (one actuator) Of course, that means that a huge headroom is available. If a certain application needs more actuators, an energy efficient way is to connect the actuators in series. However, if six actuators are series connected, the maximum current that can be obtained is only 0.47A. This must not be considered a safe headroom because the nitinol wire’s resistance will rise due to the positive temperature coefficient characteristic. As a conclusion, six series connected actuators will not work properly. The dynamic response of the current regulator was also simulated.

3. Results

![Figure 3. Simulated step response of the position control system. Reference - red; Output - black.](image)
Figure 4. Simulated step response of the current regulator. Reference - red; Current through the actuator - black.

Figure 5. Simulated multi-step response of the position control system without phase advance. Reference - red; Output - black.

Figure 6. Simulated multi-step response of the position control system with phase advance. Reference - red; Output - black.
Figure 7. Simulated sinusoidal signal response with phase advance. Reference - red; Output - black.

Figure 8. Simulated disturbance rejection of the position control system. Reference - red; Output - black.

Figure 9. Real step response of the position control system (inverted colour; 0.5s/div.; 1V/div.). Reference - upper trace, Signal from the position sensor - lower trace. (Long camera exposure time in order to capture a slow event using an analog oscilloscope).
Figure 10. Real step response of the position control system with overlapped traces (inverted colour; 0.5s/div.; 1V/div.).

Figure 11. Real P.W.M. signal at the gate of the P channel MOSFET of the switching transconductance amplifier; the PWM is inverted due to the use of P channel MOSFET (10μs/div.; 5V/div.). (Saturation P.W.M. not maximum even in saturation condition in order to protect the nitinol wire).

Figure 12. Test jig intermediate positions according to different reference voltages (0.6V; 2.2V; 5V).

4. Discussion
The developed cascaded control system based driver's performance was good enough to satisfy the expected dynamic performance. On the simulated step response in figure 3, the transient time for heat-up (position increasing) was around the value of 0.5 seconds and one second for cool-down (position decreasing) for four volts reference step. In the real step response test, featured on figure 10, the transient time for heating was around one second, equal to the cooling transient time. The reason was the placement of a small 12V cooler in order to decrease the cooling time. The cooler is powered when the amplified position error signal is near zero volts relative to the ground potential. Another reason why the transient time was higher is the ambient temperature. A lower ambient temperature will increase the heat-up transient time because the upper current limit can be reached sooner. The heat-up transient time can be lowered by increasing the maximum current that is allowed to flow through the nitinol wire. However, too much current can destroy the wire. For better cool-down management it is
important to use a good dynamic performance brushless DC motor cooler. The motor must have a proper acceleration in order to reach its nominal RPM in less than a quarter of a second. In the same time, an electronic active deceleration can help a lot. If the position reference voltage is increasing again, the cooler can slow down the heating process of the nitinol wire because of low deceleration. For the test jig, a 12V small profile cooler was used, thus providing a small inertia, current consumption and a good air flow. Without the cooler, the cool-down transient time is more than two times higher. Figure 9 shows no overshoot at all. This is accomplished because no integrator is used in the position feedback controller and a phase advance circuit is used. However, on figure 6 an overshoot occurred on the first rising step. This was because the current headroom was higher and the actuator was powered with the maximum current when it was cold (started form zero current) so the thermal inertia and saturation caused the initial overshoot. For the second step, because the actuator was already heated and the current headroom was lower, the response was better with almost no overshoot at all. Because of the efficient switching transconductance amplifier, the total supply current was around 70mA at 12V in saturation condition and around 30mA at middle steady state position (2.2V position reference) at an ambient temperature of 24˚C. As a conclusion, the stand-alone nitinol based thermomechanical actuator driver with a closed-loop position control system was successfully developed, tuned for the current testing application and evaluated in order to confirm it's simulated performance. Typical applications can be: small profile or space restricted positioning stages, small robots, low profile positioning actuators and even actuators for servo valves [4].

5. References

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