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Discrete binary muscle-like actuation with motor unit overpowering and binary control strategy

Glenn Mathijssen^{1,2*o}, Raphaël Furnémont^{1*}, Elias Saerens¹, Bram Vanderborght¹

Abstract—On novel actuator research in the field of cellular muscle-like actuators, skeletal muscles are often used as inspiration due to their modular and compact design and seemingly effortless control. Amongst others, the remaining challenges to tackle are robust designs, energy consumption minimization and control strategies. We have developed a discrete muscle-like actuator, in which solenoids can be overpowered and locked to recruit springs in series. This paper describes the spring and electronics design and proposes a binary actuator segmentation for increased resolution. Next, we propose and simulate a control strategy based on a look-up table, to cope with multiple discrete inputs, uni-directional force inputs and solenoid cooling time. Currently, the actuation units and springs are modular and can be tailored easily for specific applications. The resolution is maximized without underutilization of the actuator’s capabilities, and our control strategy can currently control 12 motor units in real-time, which can be increased to 30.

I. INTRODUCTION

Although robotic systems have evolved drastically over the past decades, robotic actuators are still mostly composed of one actuator per joint, typically a geared electric motor. On the contrary, human skeletal muscle consists of many discrete motor units, recruited individually to complete complex tasks in unknown environments.

Driven by the virtues of skeletal muscle as a source of inspiration, multiple research groups have investigated multi-input muscle-like cellular actuators, driven by a variety of actuators such as piezoelectric actuators [1], shape memory alloys [2], etc. As investigated by [3] cellular redundant actuators have the ability to be fault-tolerant, whilst still being robust and in operation. Others have exploited the discrete cellular paradigm to create highly repeatable open-loop actuation systems [4]. The modular design of cellular actuators can potentially result in cheap modules, interesting for robots with different required performances in different joints.

Depending on their training, humans can excel in explosive motions or muscular endurance. Both types, however, will suffer from muscle fatigue and decreasing strength [5]. In our previous work [6] a locking mechanism is added in

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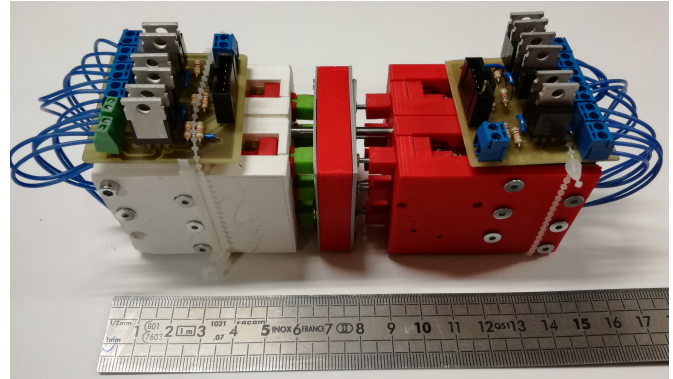


Fig. 1: The muscle-like actuator in a 6 by 2 configuration with a total of 12 lockable solenoids.

a solenoid driven series elastic actuator. In succession to our solenoid driven muscle-like actuator, equipped with laser cut leaf springs [7], a passive locking mechanism is added which enables to remain in ON or OFF position, without continuous electric energy consumption during steady-state periods. Moreover, each solenoid can be overpowered above its nominal voltage to activate stiffer springs and push the actuator performance as pursued by [8] [9] [10]. As a drawback, the duty cycle of the solenoid will be lower than 100%. Full details on the hardware platform can be found in section II. Each combination of solenoid, locking mechanism and spring is a *motor unit*, of which more can be combined to form an *actuation unit*:

- Actuation unit: the smallest module to adjust a muscle-like actuator’s.
- Motor unit: the smallest force producing device which can be controlled.

Controlling discrete multi-input cellular systems is not trivial, since these systems are highly redundant and traditional continuous control strategies cannot be used for the non continuous input signals. Furthermore, each system has its own specific features and characteristics, such as the whole body control of cross-coupled discrete cellular actuators in [11]. As discussed in [12], multi-input cellular systems run into computational problems when the number of elements increases drastically, which is traditionally solved by only changing a certain amount of inputs and calculating the difference with the previous combination.

Specific to the actuator discussed in this paper is the problem of varying availability of discrete inputs, due to the required cooling time of overpowered solenoids. In the

proposed control strategy of this paper, a desired output force F_{out} is demanded while the output position x_{out} is given. Based on a look-up table constructed by the model described in section III, produced off-line and embedded in the memory of the actuator controller, a standard and fast search algorithm can find the best recruitment combination to fulfill the required F_{out} . Each time instance, the table and the available motor units are updated. This paper proposes a binary segmentation design for increased resolution and decreased motor unit underutilization. The control strategy and segmentation are described in section IV. The simulation results in section V conclude this paper.

II. OVERPOWERING LOCKABLE DISCRETE MUSCLE-LIKE MOTOR UNITS

The lockable muscle-like actuation unit is discrete in nature. The average force bandwidth of human muscles is 2.2Hz, given by [13], and is used as a targeted force bandwidth for the muscle-like actuation unit. In addition to the virtues of human muscles, a locking mechanism is added in order to avoid continuous power consumption during steady-state periods. The locking mechanism allows each motor unit to either be in contracted or not contracted state, without power consumption. As such, only transitions between these states requires electric power.

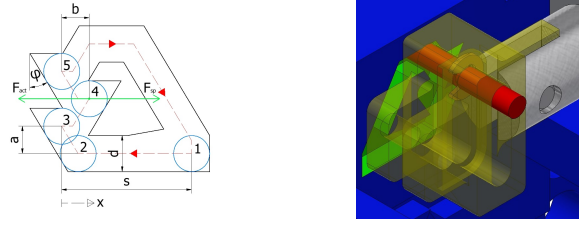
A. Solenoid powered lockable muscle-like motor unit

Each motor unit is driven by a HMF-1614z.002 solenoid from Tremba GmbH. Characteristics collected and calculated from the datasheet are listed here underneath. As described in [6], the Tremba solenoid scored best regarding strain ϵ and blocked stress $\sigma_{blocked}$ compared to 21 other commercially available models.

- Nominal Stroke s : 8 mm
- Length L : 35.5 mm
- Strain ϵ : 22.5 %
- Plunger Diameter D_p : 7 mm
- Coil Resistance R : 72 Ω
- Frontal Area A_f 0.22 $\cdot 10^{-3}$ m²

The locking mechanism required for the motor unit, requires only 2 locking positions, and locking and unlocking under uni-directional load. The locking mechanism should be passive. Via the flow-chart in [14] a cam-based mechanical locking mechanism was selected, which resembles a retractable pen mechanism as shown in Fig. 2b. The variant used in this work is non-rotational, in order to maximally exploit rapid prototyping techniques which have a high in plane precision for the green groove in 2b. The red pin travels through the green groove upon retracting and releasing from the gray solenoid plunger, resulting in locking the spring in the green groove cavities. The subsequent steps 1 to 5 indicated in Fig. 2a indicate a non retracted to retracted process, in which position 1 and 4 are the locked positions. The angle φ needs to be larger than the friction angle, which is the inverse tangent of the friction coefficient, in order to ensure a smooth operation of the locking mechanism. The groove is made from PLA with a friction coefficient for steel

of 0.4, which results in a required $\varphi = 31^\circ$. A pin of 2 mm is used which results in a backlash $b = 2.3$ mm.



(a) By means of the groove parametrization the locking mechanism is constructed.

(b) The red pin travels through the transparent yellow part, in the green groove, in order to lock and unlock the motor unit.

Fig. 2: A detailed view on the passive pen-like locking mechanism used in this work [7].

B. Overpowering spikes to increase performance

The electromagnetic device used in this work to drive the motor units, is a linear solenoid. The nominal power rating P_{nom} is determined by the heat transfer capabilities of the solenoid. The output force F_{out} generated by the solenoid can be increased by increasing the applied voltage U , according to the following (1):

$$F_{out} \propto \frac{U^2}{x^2} \quad (1)$$

In order to get a more detailed force-stroke characteristic, one should conduct a FEA including the full plunger geometry. In order to increase F_{out} passed the nominal force F_{nom} , the voltage is increased above U_{nom} which results in power ratings higher than P_{nom} . The F_{out} for different positions of the plunger x_{out} is measured for increasing voltage ($U_{nom} = 12$ V). In order to not exceed the thermal limits of the solenoid, on-time t_{on} and off-time t_{off} must be alternated, resulting in a duty cycle (DC) as given in (2). Figure 3 visualized the relation between increased voltage and DC.

$$DC = \begin{cases} 100\%, & \text{if } U \leq U_{nom} \\ \left(\frac{U_{nom}}{U}\right)^2 \cdot 100\%, & \text{if } U > U_{nom} \end{cases} \quad (2)$$

The sum of t_{on} and t_{off} results in t_{cycle} . In order to overpower a solenoid, i.e. firing with a voltage above U_{nom} , the maximum t_{on} should be determined in addition to DC. As discussed in [6], this can be done via the first-order approximation of the heat balance, based on the lumped capacitance model [15] (3):

$$mc \frac{dT}{dt} = I^2 R - uA(T - T_e) \quad (3)$$

Where m is the mass of the solenoid, c the thermal conductivity of the solenoid, u the overall heat transfer coefficient, A the external surface, T the temperature of the solenoid and T_e the environmental temperature. Using the boundary condition that the initial temperature $T_0 = T_e$, and

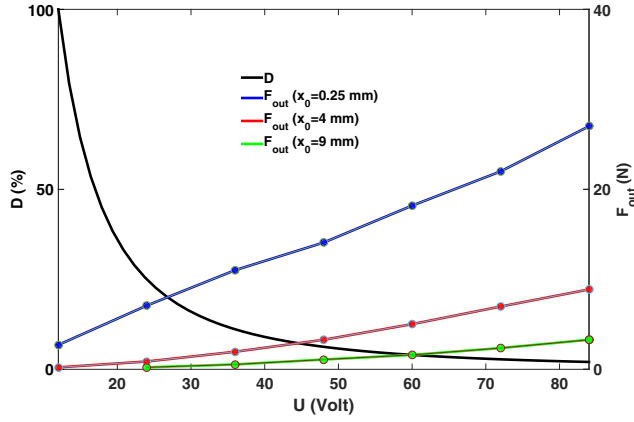


Fig. 3: The solenoid is characterized through a series of isometric experiments where for a certain position the voltage is varied and the output force measured.

$I = U/R$ an expression for the time required to obtain the maximum allowable temperature T_{max} in the solenoid using:

$$t_{en,max} = -\tau \ln\left(1 - \frac{C}{U^2}\right) \quad (4)$$

Where $\tau = \frac{mc}{uA}$ and $C = uAR(T_{max} - T_e)$

C. Spring design and implementation

In order to design a spring for the motor unit, the F_{out} at different plunger positions x is measured and represented by the dotted lines in Fig. 3. These measurements can then be used to design custom springs for each motor unit. Depending on their stiffness, the solenoids can then be fired with a certain voltage which allows the solenoids to retract.

A laser cuted leaf-spring is designed to fit the actuation unit. The design allows for a wide variety of stiffnesses to be made with only minor changes to the design drawing:

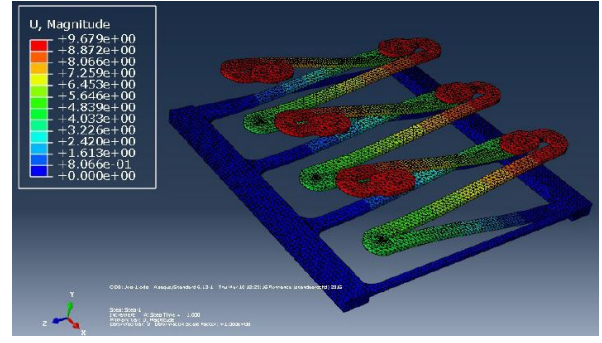
- The sheet thickness of the AISI 301 spring steel sheet can be increased for increased stiffness.
- The width of the spring lobes can be increased for increased stiffness.
- Multiple lobes can be combined in parallel, which leads to a summation of the parallel stiffnesses.

Figure 4a shows the FEA analysis of the leaf spring which is needed to tailor make the springs according to the motor unit requirements. Figure 4b shows the spring isometric measurements of 1 sheet of springs, with an additional sheet in parallel.

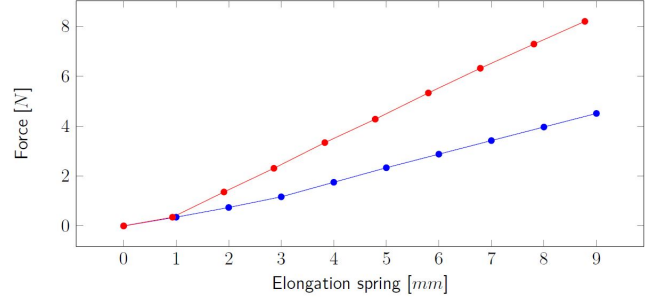
D. Electronics

The requirements for the electronics to drive the discrete muscle-like actuator can be summarized as follows:

- Variable voltage: Each motor unit can be equipped with a spring with tailored stiffness, resulting in a specific voltage which is needed to contract the spring.
- Bus line: Each actuation unit consists of multiple motor units, and each actuator of multiple actuation units. A bus line is needed to avoid excessive wiring.



(a) The leaf-spring designed for this prototype is designed in Abaqus in order to estimate the resulting stiffness when changing the width and thickness of the spring lobes.



(b) The measured force generated by the spring upon different levels of extension is measured for 1 lobe, and for 2 identical parallel lobes. It can be seen that the stiffness is approximately doubled.

Fig. 4: Detailed views on the leaf-spring design [7].

- High current and voltage: Each motor unit is fired for 25 ms when being activated and deactivated. The voltage ranges between 1 V and 100 V.

A combination of a standard PWM drive to vary the voltage, communicated to via I^2C bus line, and a custom mosfet power circuit was selected to drive the actuator.

III. ACTUATOR MODEL

This section will describe the model used for the muscle actuator. A muscle-like actuation unit can be modeled as a mass-damper-spring system. Connecting several units together in series or parallel just results in the series or parallel addition of mass-damper-spring systems together. In this paper we will only focus on the static case and thus the mass and damping will be neglected in the model. Fig. 5 depicts the schematic of the muscle-like actuator used in this paper.

The displacements of the solenoids u_{ij} are either zero or equal to the maximum stroke of the solenoids which is 8.7 mm. As such their orientation is defined towards the units to which they belong. By making a balance of the force on the two degrees of freedom of the actuator one has:

$$\begin{aligned} \sum_{i=1}^6 k_{2i} S(x_{out} + u_{2i} - x_1) - \sum_{i=1}^6 k_{1i} S(x_1 + u_{1i}) &= 0 \\ F_{out} - \sum_{i=1}^6 k_{2i} S(x_{out} + u_{2i} - x_1) &= 0 \end{aligned} \quad (5)$$

The function $S(y)$ is defined such as:

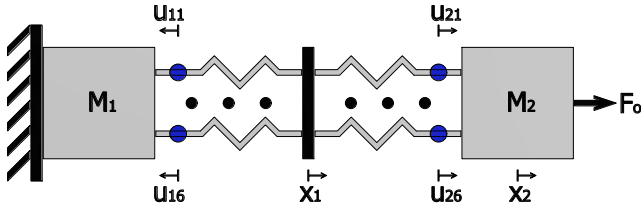


Fig. 5: M_1 and M_2 are the two actuation units used in this paper. The recruitment pattern of the solenoids is denoted by u_{1i} and u_{2i} ($i = 1, \dots, 6$). The solenoids are contracted towards the actuation units. x_1 is the displacement of the physical springs which are connecting the two actuation units and the respective stiffness of these springs are k_{1i} and k_{2i} . x_o and F_o are the displacement and force at the output of the system. Only two out of the six solenoids of each unit is represented for clarity.

$$S(y) = \begin{cases} y & \text{if } y \geq 0 \\ 0 & \text{if } y < 0 \end{cases} \quad (6)$$

$S(y)$ represents the fact that the springs can only work in extension and not in compression (uni-directional springs). As such the model is non-linear. The goal is to find, for a given output position x_{out} , the activation pattern of solenoids (hence the set u_{ij}) which results in the output force F_{out} which is the closest to the desired one $F_{out,des}$. Due to $S(y)$ solving Eq. (5) is a tedious operation which cannot be done online. Furthermore, as explained in II-B the solenoids require a certain time to cool down which the control strategy also needs to take care of. How this is done will be detailed in Section IV.

IV. BINARY SEGMENTATION AND CONTROL STRATEGY

A. Binary muscle-like actuation unit segmentation

For reasons of modularity, each actuation unit consists of the same solenoids. As described above, the solenoids used in our work are from Tremba GmbH, with a maximum nominal force F_{nom} which can be maintained when fully contracted of 1.3 N. A disadvantage of using equal solenoids for each motor unit, is a lack of diversity in different output forces. One way to increase the output force spectrum is by changing the spring stiffness of each motor unit in an actuation unit. As discussed in previous work [7] a combination of irrational spring stiffnesses enlarge the spectrum even more. Although diversifying the spring stiffness of each motor unit is perfectly possible for the spring design, as shown in section II, it leads to an underutilisation of the actuator's capabilities since most solenoids will work at lower conditions than their F_{nom} and U_{nom} .

Inspired by the work on binary segmented control of [2] on the control of shape memory alloys, we propose in this work to diversify the spring stiffness so that the motor units in one actuation unit function as a binary number. Figure 6 visualizes the idea. Some more explanation:

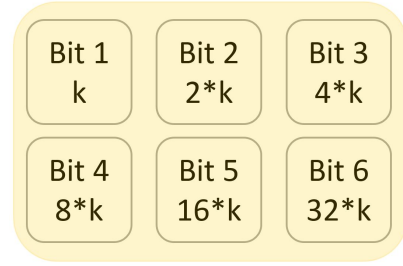


Fig. 6: A visualization of a 6 bit actuation unit with binary segmentation. The output force, and thus the stiffness, is doubled for each increasing bit.

- Total output force actuation unit = decimal form of binary number * lowest motor unit force.
- The lowest motor unit force should be equal to the nominal motor unit force.
- The maximum motor unit force is limited to the voltage by which the motor unit burns during the required on time for retracting the spring (25 ms), or by the demagnetization voltage.
- As such 00...01 equals the nominal output force of 1 motor unit, and 00...10 twice this force.

The number of unique recruitment pattern is as such maximized, since every multiple of F_{nom} (i.e. the force generated by bit 1) can only be produced by a unique binary combination, equivalent to a unique recruitment pattern.

The resolution of the binary muscle-like actuation unit can as such be expressed in as a multi-bit word, much like encoders are characterized. A 9-bit actuation unit, for example, consists of 9 motor units. The maximum binary number is 11111111 which is equal to 511 decimal, meaning the actuation unit has a resolution of 511 with a maximum force of 511 times F_{nom} .

Besides the diversified actuation output force, another key advantage is that no solenoid is underutilized since all motor units are activated by voltages higher than their nominal voltage. As a result, however, only the weakest solenoid has a DC of 100% since it can be activated and deactivated continuously as shown in Fig. 3. Bit 5 of the actuation unit based on our solenoid is designed with a stiffness $k_5 = 5*k_1$. This results in a required solenoid voltage, which can be derived from the measurements in Fig. 3. The required voltage results in the required DC according to (2). Combined with the required t_{on} of 25 ms the required t_{off} is determined.

B. Control strategy

The muscle-like actuation unit is discrete and redundant in nature. Moreover, the available actuation units vary in time due to required cooling time. As a result, real-time control of such a system is not trivial. In order to solve this, we propose a look-up table approach. The look-up table consists of the different static states of the system, for each activation pattern, and can be calculated offline, prior to operation, and application independent. An example is given in Fig. 8. The

	Voltage	k (N/mm)	Duty Cycle (%)	Cool down time (s)
bit 1 --	12	0.09	100%	0
bit 2 --	14.5	0.18	68%	0.01
bit 3 --	25	0.36	23%	0.08
bit 4 --	45	0.72	7%	0.30
bit 5 --	87	1.44	2%	1.17

Fig. 7: An example of a 5 bit actuation unit based on the solenoid used in this work. The output force, and thus the stiffness, is doubled for each increasing bit. The resulting output voltage and, duty cycle and cool down time are given in the table

...
*111	F_71	F_72	...	F_7n
*110	F_61	F_62	...	F_6n
*101	F_51	F_52	...	F_5n
*100	F_41	F_42	...	F_4n
*011	F_31	F_32	...	F_3n
*010	F_21	F_22	...	F_2n
*001	F_11	F_12	...	F_1n
	0	0.1	...	x_max

Fig. 8: The look-up table is updated every time instance to keep track which combinations are allowed in the upcoming time instance. In the example here underneath the red combinations are not allowed since solenoid on bit 2 in yellow has been activated recently and is still cooling down.

columns of the look-up table consist of output position x_{pos} and the rows of different binary combinations. The table values are force values F_{out} . The combinations indicated in red are invalid during that time instance, since it requires a change of the bit in yellow which is still cooling down.

Each time instance, the control algorithm follows the path in Fig. 9. Considering x_{out} is given, the column of the table is defined. Next, a search algorithm searches the closest F_{out} to the $F_{out,des}$, which fixes the row. This defines the recruitment pattern which will be send to the actuator, since each value which is left in the look-up table is a feasible pattern. Next, the look-up table is updated by disabling certain solutions and re-enabling certain others. The cooling times are updated then as well by subtracting a time step.

The control strategy is limited by the number of motor units, since the table will only increase in size. A 10 bit actuator requires a table of thousands of bytes, a 20 bit actuator requires hundreds of Mbs, finally a 30 bit actuator requires Gbs. Vastly increasing the number of motor units more will result in memory problems. Moreover, the speed of the search algorithm to find the the closest F_{out} requires more time with increasing motor units as well. In our set-up the loop time takes 10^{-4} for 12 solenoids, on a standard Dell PC.

Increasing the number of motor units results in an increased resolution and output force range. The number of unique static activation patterns increases as well exponen-

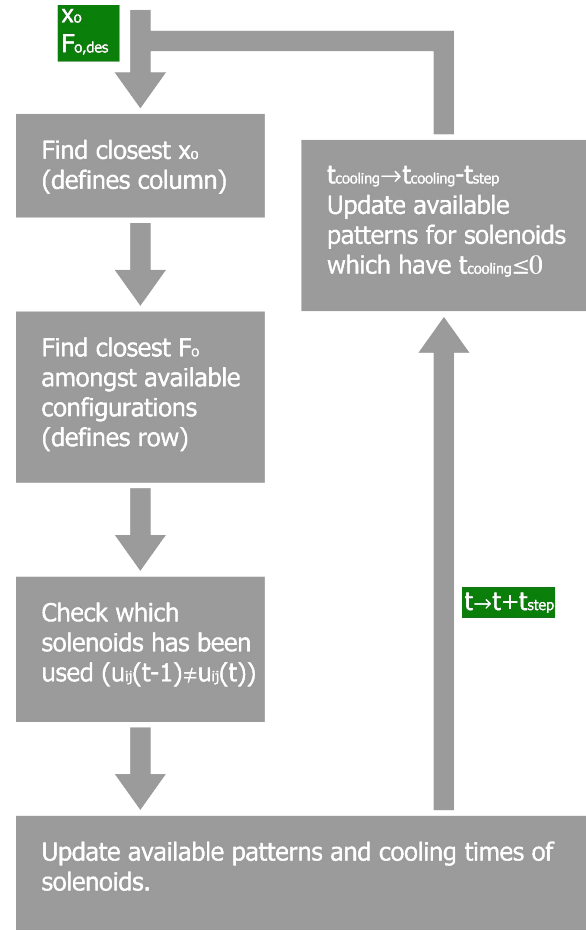


Fig. 9: The depicted method is executed every time instance to track a certain desired output force $F_{out,des}$

tially. As a result, the memory size of the look-up table increases as well. In order to find a desired set-point, the number closest to this set-point in the table should be found in the order of milliseconds, in case real-time control is required.

V. EXPERIMENTAL RESULTS

In order to verify whether the control strategy works, and to study the capabilities and limitations, a trajectory tracker is simulated in Matlab. The system consists of two 5 bit actuation units, designed according to Fig. 7, facing each other. Three F_{out} sine chirps with different maximum voltage are being tracked. The results are shown in Fig. 10. The blue and biggest of three sine chirps reaches the maximum actuator force. It can be seen that the blue tracked curve is accurate during the beginning of the experiment, though diverts once the frequency increased. This is mainly due to the fact that the higher bit solenoids are used to reach the maximum force, and thus have a longer cooling time. The lower green and lowest red curves are able to track higher frequencies, since the highest bit solenoids are not activated.

In the lower force regions the tracking is less accurate due to the resolution of the actuation unit. The upper parts of the

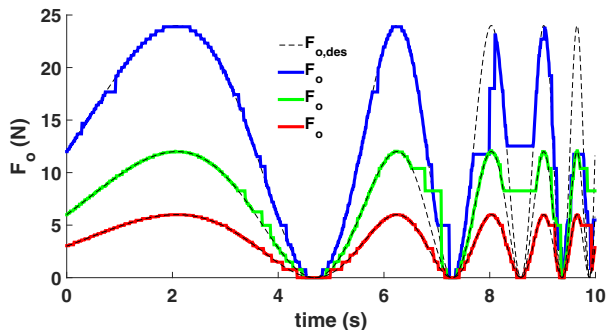


Fig. 10: The muscle like actuator control strategy is used to track a certain predefined trajectory in real-time. As can be seen from both experiments, the experiment at higher frequency results in a less accurate tracking since the solenoids cooling time limits the tracking capabilities.

sine wave are tracked more accurately than the lower parts.

Standard Matlab functions are being used to implement the search algorithm.

VI. CONCLUSIONS AND FUTURE WORK

This paper presented a discrete muscle-like actuator, which recruits springs driven by solenoids. By means of overpowering the solenoids and locking them into their static states, it is shown that underutilization of the solenoids and maximization of the number of unique recruitment patterns is achieved. The tracking simulations conducted show good approximation of a continuous force profile. Future work consists of increasing the robustness and production reliability of the actuation units in order to conduct further experiments to benchmark the control strategy.

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