**Linear One-to-Many (OTM) system**

Many degrees of freedom independently actuated by one electric motor

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**Abstract**— We report on progress on the “One-To-Many” (OTM) concept that allows a single electric motor to store energy in the form of elastic potential energy to drive multiple (e.g. hundred) motor units or independently controlled mechanical degrees of freedom. Critical to this concept is the OTM architecture which utilizes light weight, high-speed, energy efficient, robust, and cost-effective clutches that provide positional feedback. Here, we address linear springs as elastic mediums for energy storage and bi-stable solenoid based clutches that require minimal energy to transition between states. We analyze the power transfer of the system, discuss current and future designs and suggest avenues for potential applications of this practical technology.

I. INTRODUCTION

As robotics research and development continues to emerge as an important field, a practical method of actuation becomes more critical and should not go unfound. OTM takes a step in this direction by offering an alternative to conventional methods of linear actuation by minimizing the number of electric motors in a system, hence relaxing the power, mass, dimensions, and cost of the system [1].

The One-to-Many architecture is an analogous mechanical equivalent to a hydraulic or pneumatic system. The electric motor acts as the pump/compressor and the energy is stored and distributed through a series of elastic elements rather than by pressurizing fluids. The storage and distribution of mechanical energy is controlled by light-weight, high-speed, energy efficient, robust, and cost-effective clutches, the system’s fluid valve equivalent.

An OTM system provides independently controlled actuation to many degrees of freedom from a single electrical motor. However, the OTM system is quite different from an under-actuated robotic system where a single motor dependably actuates many degrees of freedom. A typical example of this type of system is a prosthetic hand with elastic finger joints that are all actuated by a single motor; mechanical degrees of freedom will independently comfort to the shape of the grasped object, but actuation is not independent [2-3]. In other words, if there are N degrees of freedom, e.g. \(X=[x_1, x_2, x_3, \ldots, x_N]\), then the actuation can be represented as a single actuation \(f\) that is then passively and dependably distributed to each degree of freedom as \(f_1(x_1), f_2(x_2)\ldots f_N(x_N)\). However, for an N degrees of freedom OTM system, there are N truly independent actuation points \(f_1(x_1), f_2(x_2)\ldots f_N(x_N)\). Hence, in terms of independence, each mechanical degree of freedom of an OTM system is actuated as it would be if actuated by an independent actuator.

Two different applications for the OTM may be very dissimilar, so it modular in that it allows for connections both in parallel and in series and hence can be utilized for a wide range of applications.

A single OTM system could be shared across multiple devices by using a customizable connector system to the points of desired actuation. The major constraint considered during the design process was the minimization of energy consumption and maximization of portability while meeting the force requirements specific to various applications.

The use of elastic elements in robotics, prosthetics, orthotic braces, and exoskeletons to achieve energy storage, variable mechanical impedance, and passive joint support was established over 50 years ago by robotics pioneers with the aforementioned elastic robotic hand and other early devices such as the passive-dynamic walking devices built by McGeer over 20 years ago [4]. A recent application of the ideas developed by these researchers is the lower-extremity “quasi-passive leg exoskeleton” built at MIT that significantly reduced the wearer’s Cost of Transport (COT) by providing passive load support through the use of mechanical joints and springs to increase mechanical impedance [5].
The “one-to-many” effect has been explored by other methods in the past, one example of this is an arm-type robot built at Nanyang Technological University in Singapore, which used a series of electromechanical actuators to engage and disengage rigid gears from one another [6-7]. While this approach is very robust and uses well-established engineering principles, it places all engaged loads upon the single motor at once, and all of the power throughout the system at any point in time is limited to the maximum output power of the motor itself. An alternative approach utilizing thermally-activated joints which could engage and disengage from a single actuator was explored at MIT [8]. Although this system has a less rigid system of engagement, it still connects the load directly to the motor. The OTM presented here is different from these and other approaches because it does not ever connect the load directly to the single electric motor; instead, elastic elements are filled with potential energy by the motor, which is then passively stored until the energy is needed at the point of actuation. Hence, power output at each degree of freedom is not limited by the maximum output power of the motor itself.

The OTM and Series Elastic Actuators (SEA), [9], share the same advantage of separating the load and motor with an elastic medium. However, in difference to an SEA: 1) a single OTM's electric motor independently actuates many degrees of freedom and 2) an OTM's motor never engages a spring simultaneously while the spring engages the load. The major constraint considered during the design process was the minimization of energy consumption and maximization of portability while meeting the force requirements specific to various applications. The more advanced OTM prototype presented here has identical modular architecture to the previous prototype, Section 2, but utilizes improved clutch technology and a more advanced control system, Section 3, allowing for larger loads and finer control as well as for more robust and more energy efficient performance. In Section 5, we discuss current and future designs and suggest avenues for potential applications of this practical technology that ranges from biomedical, space, military, industrial robotics, arts/entertainment, 3D-internet, haptics etc.

II. LINEAR OTM ARCHITECTURE

The OTM architecture comprises a modular structure where each module adds one actuated degree of freedom to the system in which it is implemented. This allows for simple assembly of an OTM system based on the desired degrees of freedom and anticipated load dynamics.

Each module consists of two gears which are axially constrained to two pulleys and connected to each other by elastic bands and two electromechanical solenoid clutches. Based on the current solenoid specifications, each module is at least multiple times less expensive and several times lighter than an electric motor actuated system with the same power specifications.

The energy is stored by disengaging the first of the two clutches, allowing the elastic element to be stretched by the motor, with the second clutch being used as the reference attachment point. The first clutch is then engaged, trapping the elastic potential energy, and storing it passively for as long as desired. When it is time for the energy to be distributed to a load, the second of the two clutches disengages, allowing the elastic element to return to equilibrium, now using the first clutch as its reference attachment point. This creates a pulling force in the cable, which can be complemented in a mechanical joint with a second motor unit for antagonistic muscle function [10].

The OTM concept allows for a build-up of energy over time that can be then released over a shorter period of time, thus providing for much larger power output to a load than the motor’s generated power input. Figure 1 depicts the overall architecture for OTM. The essential elements are the single electric motor, the force distribution and storage system, and the points of actuation.

Because each degree of freedom will be acted upon by an elastic element in a manner similar, but not identical to that of a Series Elastic Actuator, a biologically inspired actuation method can be achieved by putting several OTM motor units onto a single joint, allowing for variable mechanical impedance and different joint torques, assuming that each motor unit is placed at a slightly different joint attachment site [11-12].

![Fig. 1. The main components of OTM.](image)

III. PHYSICAL PROTOTYPE

Several experimental OTM platforms have been built and used for testing the feasibility of the technology. Here, we discuss the most recent version, with similar architecture as the previous version but with several important improvements in control and mechanics.

A. HARDWARE LAYOUT

In this particular iteration of the design, we utilize a single motor connected to three independent motor units. A motor unit consists of two clutch mechanisms and an elastic
element. This allows three possible states: Charging (when the mechanical energy is transferred from the motor to an elastic element), Neutral (when energy is stored, passively constrained by the clutches, and unconnected to the motor and load), and finally, Release (when the potential energy of the elastic element is connected to the load and transferred to it). The hardware is fastened upon a piece of acrylic for demonstration purposes and easy of analysis. Here, as shown in Figure 2, there are six clutch mechanisms (left, right), three elastic elements (center), and one motor drive-wheel (left). The springs to demonstrate the actuated release (right) represent a load placed upon the system.

Fig. 2. C1, C3, C5 are the energy storage clutches. C2, C4, C6 are the energy release clutches. Input is the motor drive wheel to charge springs. E1, E2, E3, are storage springs. E4, E5, E6 are experimental load springs.

B. CLUTCH DESIGN AND IMPROVEMENTS

The biggest problem to solve during the design process was the realization of a low-cost, low-energy use, and fast-acting clutch mechanism, one that would maintain its last state after power was removed. Many different early prototype clutches were built (Figure 3); several met some of the design requirements, but none satisfied them all.

Fig. 3. A) bead and fork clutch, B and C) CAD and physical claw-gripper clutch, D) sliding slot clutch, E) electromagnet clutch design 1, F and G, electromagnet clutch 2, physical model and CAD prototype.

All of the previous clutch designs used a bead-crimped cable to create “stops”, but these cables were problematic because they would tend to become stuck on other system parts, rendering the system unreliable. The current solution (Figure 4) does not use a beaded cable. The rotation of a toothed-pulley is fixed to the linear motion of the cable, so the pulley adds “stops” to every section of the cable. The distance between the “stops” is proportional to the distance between the pulley “teeth”. These teeth can be finely spaced, making fine release control possible. Stopping the pulley’s rotation is accomplished with a latching solenoid, a type of solenoid that employs a permanent magnet to hold it in a retracted state, and a spring to hold it in an extended state. These states can be toggled with a very short (e.g. 10 milliseconds) electrical pulse. Because of this solenoid feature, it can remain in its current state even after power has been removed, so power is therefore only needed to switch clutch states, not maintain them. This enables the system to encompass many desirable qualities without additional energy costs because mechanical energy can be stored without energy usage.

C. CONTROL SYSTEM

Here, as a proof of concept and for demonstration purposes the OTM is managed by a microcontroller board based on an Atmega AVR chip. The microcontroller is used in conjunction with an array of low-current solenoid drivers to relay the small logic-level signals from the microcontroller to the slightly higher current signals required by the solenoids. These drivers were capable of providing the bi-directional power output necessary to toggle a solenoid’s state from extended to retracted or vice versa.

A short, 10 millisecond pulse generated by the microcontroller and amplified by the solenoid driver board is sufficient to invert the state of the solenoids. The process of “charging” the elastic elements is then made possible by implementing a program (in this case within a C development environment) that outputs a binary sequence of timed on/off commands to each solenoid. For all practical applications, solenoids control can be handled by a miniaturized low-level logic circuit.
Control of the single electric motor that generates the energy to be stored in the elastic elements is accomplished using a single Pulse-Width-Modulated (PWM) channel from the microcontroller to the Maxon motor driver board. The Maxon board is configured with a simple custom-made code script that allows it to vary the motor’s velocity according to the signal which varies between 0 and 255. The motor can be started and stopped as desired to optimize energy consumption. The control needs for OTM are minimal and can be handled by very simple circuits.

IV. PERFORMANCE AND RESULTS

Preliminary tests showed that elastic energy can be easily stored in springs and that the energy input versus output can be controlled over time to create customized power output characteristics. An experiment was performed where the OTM’s single electric motor loaded elastic potential energy into the three energy storage springs. This energy was held for 500 milliseconds to demonstrate passive storage, and then released from each spring individually by the clutch mechanisms. To act as a load, three additional springs of the same type were secured to one end of the OTM and connected with cables to each actuated OTM DoF.

The initial state of the load springs was relaxed. As each DoF released energy into its respective load, the action was recorded using a camera recording 240 still images per second with a linear measuring tool placed across the whole system as a length reference. The video was analyzed frame-by-frame and the critical spring elongation vs. time data was recorded. From this data, each of the energy storage and load spring’s elastic potential energy as a function of time was calculated. Finally, the data was plotted as a time derivative to show the OTM’s instantaneous power output (Figure 5).

![Fig. 5. Input and output power. Negative function is power input; positive functions are power output.](image)

From this plot, it can be seen that the electric motor can provide a smaller power output over a longer duration of time, and that the springs provided much higher power outputs over different time durations. This demonstrates how potential energy can be released over different durations to achieve higher or lower power output depending on the application’s need. The sum of the areas of the three output functions was negligibly less than the area of the input function, showing that the OTM loses very little energy in the storage and release process.

This is the OTM’s advantage over most systems with one electric motor per one degree of freedom, i.e. One-to-One (OTO) systems: energy efficiency. Although the utilization of energy efficient clutch mechanisms (which only require energy to change their binary state from locked to unlocked) reduces energy consumption, the greatest contributor to system efficiency is obtained by separating the electric motor from the load with a controlled length of elastic element; a setup is achieved where the motor never plays the role of the passive element.

This improves system efficiency greatly due to the: 1) actively controlled passive force support/actuation (the motor is always entirely disengaged from the load), 2) the ability to accommodate the electric motor’s optimum operating conditions, and 3) its low-friction rotational mechanism architecture.

An OTM degree of freedom’s equilibrium position can be adjusted, allowing for nearly any joint state to be maintained without energy input. Furthermore the motor can be completely disengaged from the system without affecting load-bearing properties; therefore the motor never needs to input torque to keep a DOF stationary. Additionally, the motor’s efficiency can be optimized because the motor never directly engages with the load; instead, it is pumping energy into a discreet number of elastic elements. Because of this pre-known condition (i.e. one spring, two springs, etc.), no unexpected torques can be encountered, hence the motor may always rotate at a torque and velocity optimum to its electrical performance curves.

Finally, an additional experiment involving the position-controlled release of the stored energy was also conducted,
where the toothed-pulley was stopped at several intermediate points during the full release phase by pulsing the solenoid with a 10 Hz signal, which causes it to extend and retract ten full times in one second. However, the number of times that the system could be intermittently stopped is a function of spring tension (which correlates to release velocity), number of teeth on the pulley per radian, and finally the maximum oscillating frequency of the solenoids. A rotary OTM system is under development with friction based clutches that would provide a large number (e.g. thousands) of stop points during a controlled release.

V. CONCLUSIONS AND FUTURE WORK

There is a large potential for the development and application of OTM technology, and the concept is still in a relatively early phase. Currently, a new model is in development, and transforms the system architecture from linear to rotary. This system is more compact and robust. Additionally, the new design incorporates a more refined means of a controlled release so that the energy outputed from the system will have a finely controlled output with variable speed and force. In the case of both linear and rotary OTM system architecture, the energy stored in the elastic medium is defined by the position of the end points of the elastic medium. In the linear case, the end points are limited by finite dimension of allowed linear space. In difference, the rotary OTM system operates in the unlimited rotational space and hence provides more relaxed conditions for control of the system and does not require an automated mechanical reset, allowing for 100% duty cycle operation, introducing the possibility of much greater performance.

The applications for this device will be numerous, with especially attractive implications for haptic feedback, soft-orthotics, space travel (by providing active garments to astronauts in order to prevent zero-gravity muscular degeneration) and light-weight robotics. The OTM is particularly applicable to biomedical applications, specifically in the direct treatment of patients. A system of soft and wearable actuated garments would be invaluable for the treatment of physical ailments and rehabilitation.

This idea can be extended to include both assistive and resistive exercise for healthy individuals. The OTM is already supportive of this, being able to transmit forces through non-rigid structures using Bowden cables. A soft orthotic actuated shoulder brace [13-16] was built and successfully actuated using cables identical to the ones used by the OTM system.

Based on the envisioned OTM technology and the current prototype, we anticipate that it will be an excellent opportunity to reduce the gap between research results and innovative applications for practical robotic applications.

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