Fast, strong and compliant pneumatic actuation for dexterous tendon-driven hands

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Abstract—**We describe a pneumatic actuation system for dexterous robotic hands. It was motivated by our desire to improve the ShadowHand system, yet it is quite universal and indeed we are already using it with a second robotic hand we have developed. Our actuation system allows us to move the ShadowHand skeleton faster than a human hand (70 msec limit-to-limit movement, 30 msec overall reflex latency), generate sufficient forces (40 N at each finger tendon, 125N at each wrist tendon), and achieve high compliance on the mechanism level (6 grams of external force at the fingertip displaces the finger when the system is powered.) This combination of speed, force and compliance is a prerequisite for dexterous manipulation, yet it has never before been achieved with a tendon-driven system, let alone a system with 24 degrees of freedom and 40 tendons.**

I. INTRODUCTION

The unique capabilities of the human hand have long inspired roboticist in their pursuit to develop manipulators with similar "dexterity". We use this term here to refer to a combination of features: many independently-controlled degrees of freedom (dofs), speed, strength and compliance. Simple and isolated tasks such as grasping can of course be accomplished by simpler devices. Nevertheless if robots are to perform a wider range of tasks in less structured environments than what is currently possible, they are likely to need manipulators approaching human levels of dexterity.

The specific motivation behind the work described here was somewhat accidental. We purchased a ShadowHand [1] with the goal of developing and testing advanced control schemes for object manipulation. After experimenting with it briefly we concluded that, at least for the unit we received, the actuation needs to be substantially faster and more compliant in order to support dexterous object manipulation. We then disconnected the actuators (air muscles) and observed that, when we pulled on the tendons manually, the resulting finger motion was very fast and compliant. Thus we decided to return the built-in actuation system and develop an alternative. Upon further reflection it became clear that such a development is very much needed in the field. Indeed there exist multiple tendon-driven hands (including the Utah-MIT hand [2], the ACT hand [3], as well as cadaver hands [4]) that are comparable to human hands kinematically, yet the lack of suitable actuation has hindered control applications. Furthermore, 3D printing technology has made it surprisingly easy to design and build new hands (and possibly other mechanisms) with large numbers of joints and tendons attached to them – see below. The question then is, how does one pull on all the tendons. Here we offer a solution which we believe is quite universal and reflects the state-of-the-art in actuation technology.

The rest of the paper is organized as follows. In the next section we outline the design considerations and the choices we made. We then describe the design of the new actuation system in detail, followed by experimental results characterizing speed, strength and compliance of the improved ShadowHand. Finally we consider future simplifications which could make the system considerably less expensive while preserving its advantages. We also summarize the application of our new actuation system to an independently developed 20 dof UW hand [5].

II. OUTLINE OF DESIGN CONSIDERATIONS AND CHOICES

The requirement for high dexterity naturally leads to the choice of pneumatic actuation. Indeed this may be the only available technology that combines speed, strength and compliance on the mechanism level with small and lightweight actuators – in turn allowing portable drives with as many as 40 units to be built (the ShadowHand has 40 tendons). On the other hand, the built-in actuation system in the ShadowHand was pneumatic and did not meet our expectations. This however can be attributed to factors that can be avoided, as follows.

First, in order to obtain sufficient force from small air muscles, one has to mount them so that they are pre-stretched – meaning that even when the system is inactive there is a lot of passive "co-contraction". Since the tendons unavoidably slide over multiple surfaces, putting them under tension causes so much friction that the compliance advantage of pneumatic actuation is lost. Another example where passive tensioning increases friction is the ACT hand, where the electric motors need to be augmented with springs so as to prevent the tendons from slipping off pulleys (the ShadowHand does not use pulleys). The solution then is simple: replace the air muscles with air cylinders which do not need tensioning. One caveat here is that most cylinders have pneumatic seals with unacceptable friction levels. However we found a cylinder (AirPel [6]) that is effectively frictionless, weighs 46 grams, and generates 42 N of linear force at 100 PSI.

Second, the ShadowHand uses small inexpensive valves mounted on-board. Such valves have insufficient flow rate – resulting in sluggishness that matches the reputation pneumatic systems have in robotics. Yet nowadays one can find qualitatively better valves: fast, proportional, and with high flow rate. We selected the FESTO MPYE series, although there may be

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other comparable choices. To be clear, there is no perfect valve at the moment. Apart from the higher price, high quality valves are large and must be mounted off-board. This alone is not an issue (given that the compressor is also off-board), but off-board mounting means that there is an air line between the valve and the cylinder, and the longer the line is the slower the actuator becomes. However, for the combination of line lengths, flow rates, pressures and cylinder volumes used here, we were able to achieve maximum force in the cylinder around 10 msec after sending a command to the valve – which is faster than the response of human hand muscles to neural input.

Another deviation from the ShadowHand design is that we attached a linear magnetic sensor to each cylinder. Even though the ShadowHand has a joint angle sensor in each dof, we reasoned that sensing the cylinder positions directly is useful for avoiding tendon slack and also calibrating the tendon moment arms; and that other hands may not have joint angle sensors – indeed we have already built an alternative hand (UW Hand [5]) which falls in the latter category. Overall, our philosophy was to design and build the best-performing actuation system we could afford (on a budget of $60,000). This includes a National Instruments PXI systems allowing us to sample 48 pressure sensors at 32KHz and 48 linear position sensors at 9KHz and average within batches, resulting in very low noise measurements. Later in this paper we discuss options for building a less expensive system with similar performance.

III. DESIGN OBJECTIVES

We envisioned our system to be a general purpose actuation module capable of actuating most pneumatically driven robots, with an added emphasis towards tendon driven systems. The intended use is limited to research settings at the present level of development. Design choices listed below (in decreasing order of priority) were made while designing the system.

1) Compatibility with requirements of most pneumatically driven robots with focus towards tendon driven systems
2) Minimum hardware bottlenecks
3) Maximum computational capability
4) Use of off-the-shelf parts
5) Modularity in design at all levels
6) Accommodate extensions and facilitate modifications at all levels
7) Intended use under research settings
8) Safety
9) Weight
10) Cost

IV. DESIGN

The hardware (Fig 1) consists of the following modules:

1) Actuation unit
2) Pneumatic control unit
3) Electronics unit
4) Computational unit

Out of the four units, only the actuator unit is specific to the robot being driven by the system. Presently this unit is configured for tendon driven hands. However, it should be noted that the actuator units bear no restriction towards tendon driven systems. All actuation mechanisms (tendon driven/ direct actuation) under all configurations (single/double acting, bundled/ distributed) are supported. The last three modules can be used for any pneumatically actuated system with appropriate configuration of the actuator unit.

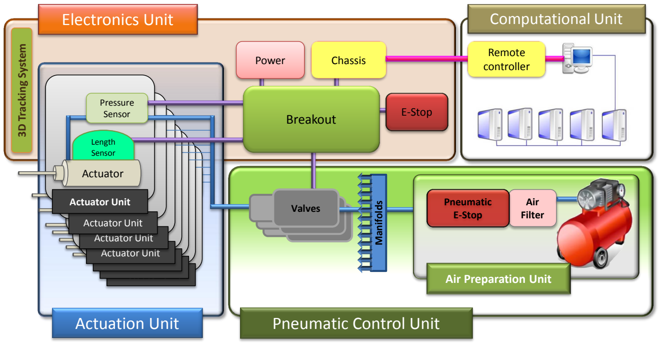


Fig. 1. Hardware design schematics. Air pathway is represented using blue lines. Electrical pathway is represented using purple lines. Digital data pathway is represented using pink lines.

V. ACTUATION UNIT

Presently, the actuation unit is configured as a tendon driven hand, thus we call it 'Muscle Actuation Unit'. It consists of the following sub-modules

1) Hand muscles actuation unit
2) Arm muscles actuation unit

In addition to the above, the muscle actuation unit houses two components of electronic units - the pressure and length sensor. These are discussed in detail in section VII.

Muscles acting over the finger and wrist tendons form 'hand muscle actuation unit' . It consists of Actuator units, and Housing assembly. Muscles acting over the lower arm, elbow, upper arm and shoulder form 'Arm muscles actuation unit'.

A. Actuator unit

Design parameters: The selection of actuators was based on the design parameters listed below in decreasing order of priority.

1) Minimum friction and stiction
2) Maximum force output
3) Fast with minimum response time
4) Minimum weight of actuators
5) Compactness of actuator unit
6) Compatibility with sensory devices
7) Availability in different configurations for different use cases
8) Durability

It should be noted that these principles focus on generic actuation mechanisms. No restrictions specific to tendon-driven systems were made.

Hardware details: The actuator unit (Figure:2) consists of double-acting Airpel series cylinders commercially manufactured by Airport Corporation. Single-acting cylinders are often air-return or spring-return and do not allow control over the return force. Double-acting cylinders were selected for complete control over the actuation force in both directions (although this feature is not yet utilized). The finger tendon's actuator unit has stroke length of 37.5mm, can produce up to 42N of force and weights 45.7grams. The wrist tendon's actuator unit has stroke length of 50mm, can produce up to 125N of force and weights 95.7grams. Detailed specifications can be found at [6].

Double-acting modules were used in single-acting mode in the Muscle Actuation Unit. Finger tendons were actuated using M9 cylinders and wrist tendons were actuated using M16 cylinders. In tendon driven systems, it seems preferable to have a small force on the actuators to avoid tendon slack when the muscles are in passive non-pulling state. However, the non-zero force from the passive tendon creates co-contraction and adds undesirable stiffness to the joints. The return force of single acting cylinders are fixed and non observable and cannot be compensated using pneumatic forces since both forces act in same direction. Double-acting cylinders with no return were employed to simulate virtual variable stiffness springs to intelligently handle tendon slack and minimize joint co-contraction. Variable stiffness simulated springs facilitated control over the return force which would not have been possible if single acting cylinders were used. For compatibility with length sensors, magnetic cylinder pistons were used.

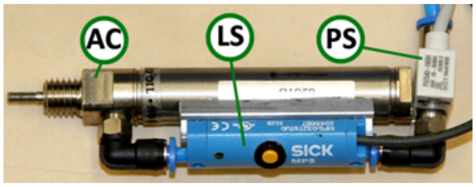


Fig. 2. Cylinder unit [AC: Actuator, LS: Length Sensor, PS: Pressure Sensor]

Design evaluation and experience: The actuator selection was the most critical and challenging selection of the entire design. More than 16 models from 6 different manufacturers were rigorously tested over the listed design parameters. Though all the considered models performed well on most design parameters, requirements 1 and 3 were exceptionally severe.

The models from Airpel significantly outperformed others on criteria 1 and 3. The stiction and friction values for these models were exceptionally small - the piston fell under its own weight when the cylinder was not horizontal. This is possible because the traditional pneumatic seals have been replaced with "air seals" with precision-fit graphite pistons that slide freely (without lubrication) inside a Pyrex glass cylinder providing unique ability to impart smooth motion at very low pressures, slow speeds and short strokes. There is a small air leak of about 2SL/min [7], however this is not an issue when using high flow rate valves.

To sum up, the Airpel cylinder we selected rates well on all parameters except 4 and 5, on which it rates moderately.

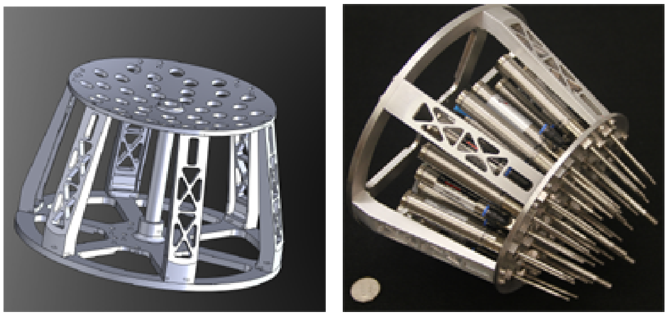
B. Housing assembly

Design parameters: The design parameters for the housing assembly are listed below in decreasing order of priority:

1) Strength, load bearing and stability
2) Minimum off-axis actuator loads
3) Compactness of Hand muscles actuation unit
4) Weight
5) Ventilation
6) Compatibility with different hands
7) Ease of component assembly
8) Machinability

Hardware details: Figure: 3 shows the final housing assembly without the actuator unit. The assembly contains 36 of the M9 Airpel actuator units for finger tendons, and 4 of the M16 Airpel actuator units for wrist tendons.

Tendon-driven robotic hands usually route finger tendons via the center of wrist joint in order to minimize the moment arms of finger tendons on the wrist joint. As a result, all finger tendons come out of the hand via an opening at the wrist. To reduce off-axis actuator loads, it is desirable to mount the cylinders so that they all point to this opening – suggesting a concave mounting plate. The back plate is free of cables and connectors and has mounting holes for attachment to a robot arm. It is compatible with the Shadow Arm robot – which we have also redesigned with air cylinders, but this will be described elsewhere. Figure: 4 shows the complete Muscle actuation unit without the back plate. Note that if we did not attach a length sensor to each cylinder (which doubles the cylinder diameter) the diameter of the assembly could be reduced roughly by half.



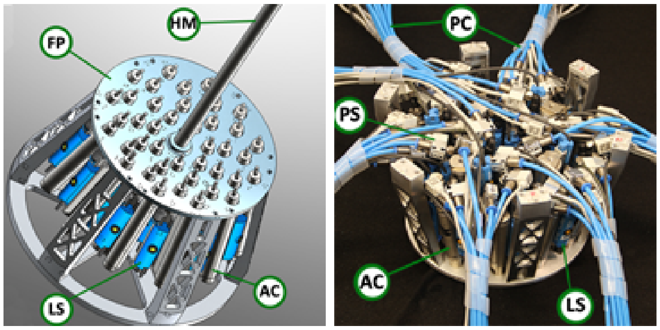
(a) (b)

Fig. 3. Housing assembly (a) CAD model (b) Final machined assembly

Design evaluation: Machining the housing assembly (and in particular the curved plate) turned out to be harder than it first appeared, but was eventually successful. It weighs 660grams, and can sustain about 75N from each actuator with a factor of safety 3. When the actuators and the ShadowHand are mounted, the entire system weighs 4.5kg. When attached to a robot arm, most of this mass is near the base (elbow), thus we do not expect it to be problematic.

VI. PNEUMATIC CONTROL UNIT

Design Parameters: For the pneumatic control unit, the following design parameters (in decreasing order of priority)



(a) (b)

Fig. 4. Muscle Actuation Unit (a) CAD model (b) Final assembly (without back plate). [FP: Front Plate, HM: Hand Mount, LS: Length Sensor, AC: Actuator, PS: Pressure Sensor, PC: Pneumatic Connectors]

were established.

1) High flow rate
2) High update frequency
3) Minimum pneumatic latency
4) Minimum pneumatic bottlenecks and avoid air pockets
5) Independent of type of actuation unit
6) Modularity
7) Facilitate modification and accommodate extension
8) Compact and light weight
9) Cost

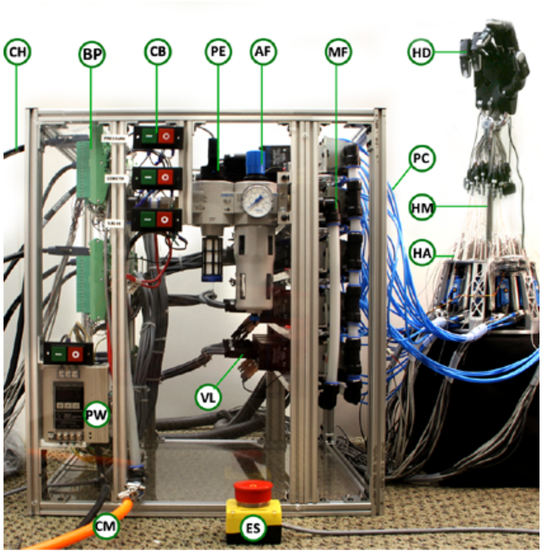


Fig. 5. Pneumatic Control Unit (2ft x 2ft x 2ft) [CH: To chassis, BP: Breakout Panel, CB: Circuit Breaker, PE: Pneumatic E-stop, AF: Air Filter, MF: Air Manifold, HD: Hand, PC: Pneumatic Connections, HM: Hand Mount, HA: Hand muscle actuation unit, VL: Valve, ES: E-Stop, CM: To Compressor, PW: Power]

Hardware details: The pneumatic control unit (Fig 5) consists of the following subunits:

1) *Air preparation module* consists of air compressor and LFR-3/4-D-5M-MAXI-A filter regulator with a flow rate of 7,600L/min at 6 bar. Detailed Specifications can be found in [8]
2) *Pneumatic control Valves*: Pneumatic control unit contains 40 MPYE 3/5 proportional valves from FESTO. Pneumatic valves (MPYE-5-M5-010-B) used for 'Hand muscle actuation unit' have a flow rate of 100l/min at 6bar, bandwidth of 125Hz and weight 290g. Detailed specifications can be found at [8].
3) *Air supply manifolds*: MPYE series proportional valves were designed by FESTO as stand alone, high end devices to be used as individual units. Thus no manifold solution have been made available for these valves. After careful examination, PAL manifolds of TIGER-2000 series [8] valves were modified for compatibility with MPYE series valves. Pneumatic control unit contains 5 PAL-10-B manifolds [8], each serving 10 pneumatic control valves.

Evaluation and Experience: Proportional valves were preferred over binary switching valves despite their moderate performance on parameters 8 and 9. This was driven primarily by our application requirement that called for fine-grained control over flow rate for fast and precise actuator control.

Binary switching valves achieve variable flow rates using pulse width modulation (PWM) which restricts smooth and precise control over flow rates. Moreover, PWM frequency is limited by the bandwidth of the device, further constraining smooth behaviours. A bank of binary valves can get very loud when switching at a fast rate.

PAL manifolds are capable of serving valves with flow rates up to $2600l/min$ i.e. our manifold solution is capable of facilitating upgrades to all MPYE series models without any modification. High flow rate (20X the requirement of the presently used MPYE-5-M5-010-B model) manifolds are preferred since they act as pneumatic buffers, thus avoiding air pockets under heavy flow requirements. Our air supply manifold presently contains 2 expansion slots. Addition of manifolds for future expansion is facilitated by the high level of modularity in the design, within reasonable efforts.

Pneumatic latencies are a function of tube lengths between the actuators and the valves. The air path between them was minimized to the extent possible. Pneumatic manifolds and valves were configured to minimize the pneumatic interface (face where valves expose their pneumatic connections to actuators) surface area, thus minimising the tube length between valves and respective actuators.

VII. ELECTRONICS UNIT

The electronics unit consists of the followings components:

1) Sensors: Cylinder pressure sensors, and piston length sensors (housed by 'Muscle actuation unit' Figure:2).
2) NI PXI Chassis with multiple A/D and D/A boards.
3) Power Supply.
4) Emergency Stop.

Design parameters:

1) Sensors
   a) Observability of entire state of the system
   b) Resolution, bandwidth and range
   c) Compatibility with generic pneumatic actuators
   d) Stand alone, compact and light weight

   e) Flexibility and ease of replacement

2) Chassis
   a) Minimum latency
   b) Sensing resolution, bandwidth and range
   c) Data bandwidth for communication with computational unit.
   d) Support for multiple communication protocols
   e) Expandable and reconfigurable
   f) Support for different operating systems
   g) Compact, enclosed and safe

3) Power Supply
   a) Compatible with sensor and actuator requirements
   b) Clean and reliable
   c) Peak load capacity
   d) Electromagnetically decoupled output channels
   e) Overload protection, over voltage protection and short-circuit protection
   f) Indication monitor

4) Emergency Stop
   a) Minimum latency
   b) User and hardware safety

Hardware details:

1) Sensors
   a) *Pressure* Electronics unit contains 48 solid state SMC pressure sensor. 40 sensors are housed by 'Hand muscle actuation unit' and rest 8 by 'Arm muscle actuation unit'.
   b) *Length* Electronics unit contains 48 Sick magnetic piston length sensor. 40 sensors are housed by 'Hand muscle actuation unit' and rest 8 by 'Arm muscle actuation unit'.
   c) *3D-tracking system* consists of active marker motion tracking system from PhaseSpace. [9]

2) Chassis: National Instrument's *9-Slot 3U PXI Express: PXIe-1078* module with 1GB/s is configured as Chassis. Each slot has a bandwidth of 250MB/s. Present configuration of modules sample 40 hand length sensors at 9kHz and 48 pressure and 8 arm length sensors at 32kHz. Chassis is also equipped with 1mbps CAN module which is used to communicate with ShadowHand sensors. Computational unit uses one 798MB/s bandwidth PXIe-PCIe data channel for complete control over the chassis. Detailed specifications can be found at [10]

3) Power Supply: 24 V DC 10Amps *S8VS-24024A* switching power supply from OMRON [11] is used as power source. One electromagnetically separated channel powers the sensors while the other powers the Pneumatic control valves.

4) Emergency Stop: A hybrid combination of software and pneumatic e-stop is used as an Emergency unit. Pneumatic stop has a flow rate of 6,500 l/min at 6 bar and weighs 600gms.

Design evaluation and experiences:

TABLE I
SENSOR SPECIFICATIONS

Specifications	PSE540(A) [12]	MPS [13]
Measuring Range	0-1Mpa	32-256mm
Operational Voltage	12-24 VDC, ripple(P-P) ±10%	15-30 VDC, ripple(P-P) ±10%
Analog output	1-5 VDC	0-10 VDC
Resolution	<2%	0.05mm
Linearity	<±0.7%	0.3mm
Repeatability	<±0.2%	0.1mm
Sample Time	N/A	1 ms
Current consumption	<15mA	25mA
Output impedance	1kΩ	2kΩ
Weight	4.6g(without wires)	N/A
Max Speed	N/A	3m/s

Since the intended applications of our system was towards research applications, there was never a preference towards onboard electronics.

Designing onboard electronics can definitely make the overall system compact and independent. These advantages from design of onboard electronics would have come at the cost of reconfigurability and extendability of the hardware. Furthermore, it would have conflicted with our overall design parameter-4 of using off-the shelf components to the extent possible. All connections were made using TBX-68, a DIN rail mount screw terminal connector block from NI, for accessability, reconfigurability and debugging purposes.

1) Sensors
   a) *Pressure*: Air path adds latency to any pneumatic system. Since our actuators are driven using off-site high flow valves, pressure sensors were placed closest possible to the actuators to account for the pneumatic latency.
   b) *Length*: Length sensing capability was a difficult choice, as it posed several challenges at multiple levels. Piston length sensing capabilities were added to cater to some of our recent efforts in the direction of bio-mimetic tendon driven systems [14] [15]. In such systems, it is particularity difficult to have joint angle sensors. Access to tendon excursions helps with kinematic modeling [15].

      Size of Actuator unit: The size of the actuation unit had to be increased to accommodate for length sensing without which the diameter of the hand muscle actuation unit would have been comparable to the typical dimensions of a human forearm.

      Number of Analog Input channels: Due to high impedance of length sensors we observed *ghosting* [16] [17]. In case of ghosting, every sensor at i^{th} channel of DAQ gets coupled with the one connected to every $(i+1)^{th}$ channel. Most acceptable and efficient way to eradicate ghosting is to interleave null/ground channels between each sensor channels. Null channel interleaving completely eliminated ghosting but resulted in 2X number of DAQ channels.

2) *Chassis*: 2X AI channels were used for length sensors

to mitigate the effects of ghosting. This requirement was met by replacing one PXIe6363 module with PXIe6255 module that has more number of channels but a lower sampling frequency. This reduced the rate at which Hand actuation unit's length sensor can be sampled from 32KHz to 9Khz.

3) *Power supply*: Power is distributed via modular power strips. Individual sensors/actuation banks can be turned on/off to minimize noise floor and system load when not in use. Modular power distribution facilitates addition of different power supply units for individual sensor/actuator submodules, thus facilitating upgrades at all levels.
4) *Emergency Stop*: Control valves provide unreliable flow rates when pneumatic input is fed without operating power. Unreliable flow rates can damage the robot by pushing it outside its stability regime or setting joints into oscillations. Emergency module was designed to allows pneumatic flow input only when control valves are powered up.

   Initially, we considered a complete shutdown in case of operational emergency e.g. robot performing an undesirable movement. However, careful observations (listed below) revealed that powering down the pneumatics is a more reliable and faster option.

   - Valve charging up its actuator's pressure when emergency was triggered: Due to pneumatic buffers feeding the control valves, the actuator will continue charging up till the pressure drops in the buffers and then actuator's residual pressure flushes out.
   - Actuator is pressurized and valve is closed to maintain the chamber pressure when emergency is triggered: This pressure gets trapped in the cylinder and emergency not avoided.

   The correct way to process an operational emergency is to exhaust the input pressure by flushing out the pneumatic buffers (using a high flow exhaust port) and opening the valves to exhaust out the cylinder pressure. This requires a pneumatic shutdown while valves maintain their input operating power. For a non operational emergency, circuit breakers are provided at all levels from top, which powers down the entire system, to bottom level, which powers down individual subcomponents.

VIII. COMPUTATIONAL UNIT

Design parameters: Design parameters established for the computational unit have been listed below in decreasing order of priority

1) Reliable communication
2) Minimum communication latency
3) Maximum computational capacity
4) Maximum data bandwidth

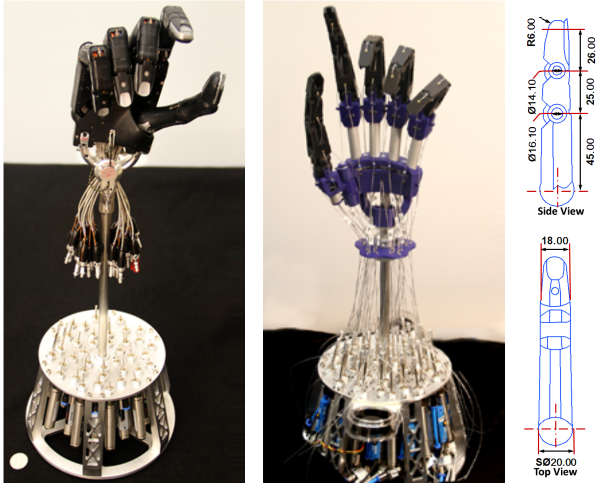
Hardware details: NI PXIe-PCIe8371, x4 MXI-Express is used to communicate with the chassis using a high bandwidth PCI Express link. Any normal desktop or server computer with PCI express slot can serve as a Computational unit. 3D motion tracking system communicates using a standard ethernet port. PCIe link is used to retrieve pressure sensor and length sensor data, and to command the Pneumatic control assembly.

Design evaluation and experiences: Data communication using PCIe link and standard ethernet link ensured that our system is compatible with any standard computer without any special requirements. Presently a 3.0Ghz AMD Phenom(tm) II X6 1075T, 8.00 GB machine with Win7 OS is used to control the system.

IX. DESIGN EVALUATION

Final hardware was evaluated on various design parameters using two tendon driven hands. Actuation system was perfectly compatible with both hand designs without modification.

1) 24-dof ShadowHand, developed by ShadowHand company [1]
2) 20-dof UW hand, being developed at our lab independent of the actuation system [5]



(a) (b) (c)

Fig. 6. (a) ShadowHand mounted on the actuation unit. (b) UW hand [5] mounted on the actuation unit (c) ShadowHand finger dimensions

A. Force and compliance

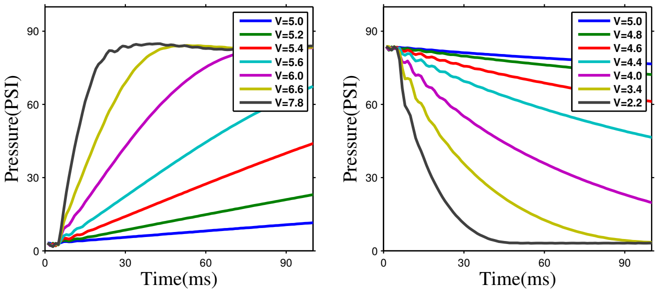
System force and compliance characteristics were studied using the ShadowHand and UW Hand. An external force of 6 grams for ShadowHand (and 8gms for UW Hand) at the index finger tip was enough to flex the MCP joint thus confirming the exceptional compliance of the final system. Typical characteristic force behaviours are summarized in Table II & III

TABLE II
ACTUATOR FORCE CHARACTERISTICS

Specification: No load connected to piston	Orientation	Force
Minimum external force to break stiction and friction	Horizontal	2.5g
Minimum external force to break stiction and friction	vertical	Piston falls under its own weight

TABLE III
HAND FORCE CHARACTERISTICS

Specification: Finger and actuators oriented vertically	Shadow Hand	UW Hand
Minimum actuation force at finger tip to move MCP joint (at atm pressure)	4.0g	2.0g
Minimum actuation force at finger tip to move MCP joint (at min slack correction pressure)	6.0g	8.0g
Maximum flexing force at Index finger tip	300.5g	705g
Maximum extension force at Index finger tip	439.4g	700g



(a) (b)

Fig. 7. (a) Pressure behaviours while pressuring cylinder from zero using valve command(V) (b)Pressure behaviours while exhausting cylinder from zero using valve command(V)

B. Actuation Speed

Our prime motivation for the development of this actuation system was to use tendon-driven hands and perform dexterous hand manipulation experiments. Any dexterous hand manipulation demands agility and responsiveness from its actuation hardware. These capabilities are evaluated in the present and the following section. The actuation system's speed capabilities were evaluated using a simple open loop bang-bang control strategy over the index finger MCP joint. The goal was to achieve full stroke movements (joint limit to joint limit) at maximum frequency. Control switching frequency was gradually increased until finger started making incomplete strokes, i.e. reversed before hitting the joint limits. Using this simple strategy, a frequency of about $7Hz$ was achieved. We are working towards a more principled way to further improve actuation speed by carefully modelling valve and pneumatics of our system. Further details are provided in [18]

C. System latency and event timings

System responsiveness was evaluated using a reflex experiment. During the experiment, small external disturbances were applied at the finger tip of the middle finger. The system was programmed to detect the disturbance (using the joint angle sensors in the ShadowHand) and react by extending the index finger. The system was found capable of detecting minute disturbances and reacting very quickly. One can consider multiple definitions of response latency. The first change in pressure is observed 8 msec after the disturbance (this corresponds to reflex latencies defined in terms of muscle activity in the biological motor control literature). See Fig 8. When measured in terms of the resulting motion, the latency is around 29 msec.

D. video attachment

A supplementary video is attached with the manuscript. The video demonstrates speed, reflex and compliance properties of the actuation system with ShadowHand skeleton. Speed behaviour is demonstrated using a sequence of flection and extension of joints (limit to limit), one at a time. Entire sequence of flexing and extension for all 24 joints merely takes 2.44 seconds. Each movement is roughly 70 milliseconds. Hand reflex is demonstrated using the experiment mentioned in subsection above. System compliance is demonstrated using 3 experiments. First, we demonstrate that actuation yields away to air blow from an average adult. Second, dead weights of 1g, 2g and 5g were dropped on the finger from a height of 5 cms to show compliance. Third, we demonstrate the effects of gentle interactions from an average adult.

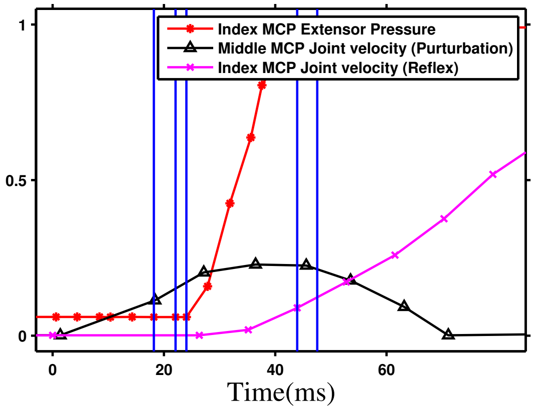


Fig. 8. Time stamps(from left to right): $T1$(Event Trigger, Middle finger MCP movement detection) = 18.179ms, $T2$(Actuation voltage written to valve) = 22.084ms, $T3$(Pressure wave arrival) = 24.044ms, $T4$(Index finger MCP movement detected) = 46.943ms, $T5$(maximum pressure at the actuator) = 47.55.

X. HOW TO MAKE THE SYSTEM LESS EXPENSIVE

The approximate cost breakdown of our present system is as follows:

Component	Unit price	Total
FESTO valves	$800	$32,000
SICK sensors	$250	$10,000
AirPel cylinders	$50	$2,000
Pressure sensors	$50	$2,000
NI PXI system		$10,000
Custom machining		$4,000

The most expensive components (and thus primary candidates for simplification) are the valves, linear sensors, and electronics. The PXI system we configured is an overkill, considering that the sensors have low noise to start with (so the high sampling rates and mini-batch averaging are not essential) and the bandwidth of the valves is only 125 Hz so there is no point in having a fast control loop (indeed we are only using 200 Hz). The National Instruments system has very mature drivers and is overall a great choice, but one could build a considerably less expensive replacement for the present purposes, perhaps using multi-channel A/D chips on custom circuit boards mounted in the forearm.

The biggest potential for savings are in the valves and position sensors. Presently we use one valve and one sensor per cylinder. This results in a universal pneumatic drive which can be used to actuate any mechanism with up to 40 tendons. Note however that 40 is actually quite a lot, and is only needed when using so-called 2N designs where tendons act on individual joints and are arranged in agonist-antagonist pairs (as opposed to the more distributed action found in the human hand and in the ACT hand). If we are willing to assume that most or all tendons will always operate in agonist-antagonist pairs, we could use one valve and one position sensor per tendon/cylinder pair (note that we still need all cylinders because even in this organization the two tendons in a pair will typically have different and possibly variable moment arms). The FESTO MPYE valves are 5/3 valves and are in fact designed to power pairs of cylinders. With these simplifications, the cost can be reduced by half. The ShadowHand skeleton (without any actuation) still costs around \$60,000. However, as shown in our companion paper [5], one can 3D-print a hand with comparable dexterity with cost of materials around \$100 and a couple of days of assembly work. Combining these two advances, it should be possible to make dexterous robotic hands whose performance exceeds any product available on the market to today, for less than \$40,000. These hands rely on off-the-shelf components and 3D printing, and could be built in academic labs.

Finally, we are not certain that proportional valves are actually needed. We clearly need valves that respond quickly and have high flow rates, but what if they were binary (and thus presumably a lot cheaper)? In principle proportional valves provide smoother movement, but given that air dynamics introduce low-pass filtering, it remains to be seen how much the performance of the (to-be-developed) control schemes will degrade in the presence of binary valves. If the degradation turns out to be negligible, this will result in substantial further reduction in the cost of the robotic hands we envision.

XI. SUMMARY

The development of the present system was motivated by our desire to solve complex dexterous manipulation problems. We emphasize that we are not building hardware for the sake of building hardware. Indeed the primary focus of our research group is control; see [19] [20] [21] for examples of recently-developed control schemes applicable to complex robots. If the robotic hardware we need already existed, we would be more than happy to focus on using it and making progress in terms of control. Unfortunately suitable hardware in terms of robotic hands does not appear to exist (with the possible exception of the DLR hand which is not available commercially), and so we were forced to develop the system described here. This development is now complete and we are ready to make a transition to control experiments. We are also finalizing the re-design of the ShadowArm robot with similar actuation, and will soon be able to mount the hand assembly on the new arm. Once the entire system is functional and used in specific manipulation experiments, we will be able to characterize its capabilities in context. But the basic tests performed here already illustrate that the system is very capable.

We hope that other research groups as well as commercial entities will be interested in building similar actuation systems. This paper contains a lot of technical details that should help in replication efforts, and we are happy to provide additional details upon request.

XII. ACKNOWLEDGEMENTS

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