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Liquid-Fueled Actuation for an Anthropomorphic Upper Extremity Prosthesis

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Abstract— **This paper describes the design of a 21 degree-of-freedom, nine degree-of-actuation, gas-actuated arm prosthesis for transhumeral amputees. The arm incorporates a direct-drive elbow and three degree-of-freedom wrist, in addition to a 17 degree-of-freedom underactuated hand effected by five actuators. The anthropomorphic device includes full position and force sensing capability for each actuated degree of freedom and integrates a monopropellant-powered gas generator to provide on-board power for untethered operation. Design considerations addressed in this paper include the sizing of pneumatic actuators based on the requisite output energy at each joint; the development of small low-power servovalves for use with hot/cold gases; the design of compact joints with integrated position sensing; and the packaging of the actuators, on-board power, and skeletal structure within the volumetric envelope of a normal human forearm and elbow. The resulting arm prototype approaches the dexterous manipulation capabilities of its anatomical counterpart while delivering approximately 50% of the force and power output of an average human arm.**

I. INTRODUCTION

AMONG the many challenges that exist in the development of an anthropomorphic arm is that of providing a high number of actuated degrees-of-freedom, each capable of significant force and/or power, in a highly confined space. As such, a critical component of any viable approach to an anthropomorphic arm is the incorporation of actuators that deliver comparable power density, force density, strain capability, and bandwidth to human skeletal muscle, and importantly, must embody a similar form factor. In fact, since unlike a human arm, the geometric constraints of a transhumeral prosthesis requires that the elbow actuator lie in the forearm, comparable performance to a human will actually require greater power density than human skeletal muscle.

State-of-the-art electromagnetic motors have a reasonable power density and a good bandwidth, but they exhibit a low torque density (relatively to human joint actuation), and do not provide an appropriate form factor for high-density actuation in an anthropomorphic form. Due to their low torque density, an electromagnetic motor requires a significant transmission ratio, typically embodied by a gearhead. Use of a gearhead reduces significantly the power density of the actuator, due to both a reduction in efficiency and a corresponding increase in actuator weight (i.e., the gearhead both decreases the numerator and increases the denominator of the power density). The net result is an actuator with a power density that is approximately three to five times less than human skeletal muscle. The combined drawbacks of low power density and awkward form factor introduce significant challenges into the development of an electromagnetic motor actuated anthropomorphic arm with near-human capability. This paper describes an alternative means of developing an anthropomorphic arm based on a chemofluidic actuation approach. The proposed approach provides the actuator power density, force density, bandwidth, and form factor conducive to the development of an anthropomorphic arm, and also provides an improved energy density relative to state-of-the-art secondary (e.g., NiMH) batteries.

II. DESCRIPTION OF THE CHEMOFLUIDIC APPROACH

The proposed approach is enabled by leveraging an actuation approach for compact self-powered systems recently developed by the authors [1-4]. This approach, which is based on the catalytic decomposition of the monopropellant hydrogen peroxide as an energy source, has recently been shown to provide a figure of merit for self-powered actuated systems that is an order of magnitude greater than state-of-the-art batteries and electromagnetic motors [3,5]. The authors have additionally demonstrated closed-loop position and force controlled versions of the monopropellant actuation approach with bandwidth appropriate for human movement. The catalytic reaction upon which the approach is based is strongly exothermic, and the resultant thermal energy is transduced to mechanical work via the expansion of the gaseous reaction products. Unlike non-catalytic combustion, this reaction scales downward well, essentially retaining its reaction efficiency even at very small scales. The catalytic reaction can in essence be considered a flow rate amplifier. Specifically, the propellant is stored in a pressured cartridge, which is

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pressured by a CO_2 cartridge. The proposed approach utilizes this pressurized propellant cartridge as the thermodynamic equivalent of a battery, with the output being a gas flow rate at a given pressure (rather than a current at a given voltage, as is the case with an electrical battery). Just as with an electrical battery, the amount of output flow depends on the downstream impedance of the load. When the downstream impedance is infinite (i.e., no actuators in use and gas valves closed), the system will not draw any flow from the fuel cartridge (technically a propellant cartridge). When the downstream impedance is lowered (i.e., by one or several valves), pressure in the cartridge forces propellant through the catalyst, which effectively increases the flow rate from a signal level to a power level (i.e., through its exothermic release of heat and resulting gaseous expansion). The effective increase in flow rate is typically two to three orders of magnitude, and depends specifically on the concentration of propellant and the downstream pressure. The pressurized gas output is used to power a set of gas actuators, wherein the gas flow for each is controlled via a four-way servovalve. This configuration is depicted schematically in Fig. 1.

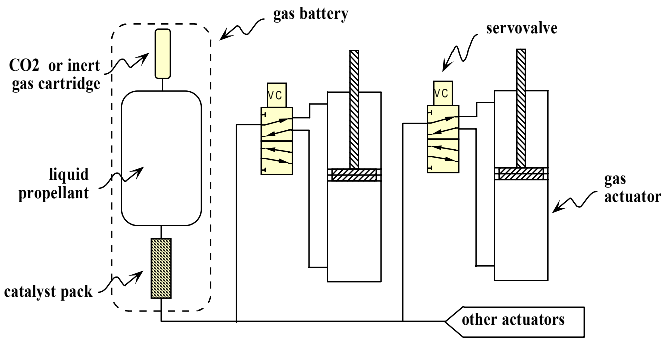

Fig. 1. Schematic diagram of proposed actuator configuration.

In addition to the previously described energetic characteristics that enable the development of an anthropomorphic arm with human-scale output capabilities, the proposed actuation approach also provides advantages with respect to the behavioral characteristics and control of the arm. Specifically, the proposed configuration exhibits an open-loop stiffness and damping similar to the human system, provides a degree of backdrivability similar to the human, and requires no power consumption for isometric contractions.

In a manner conceptually similar to the energy conversion in skeletal muscle, use of a liquid fuel enables the direct chemical to mechanical energy conversion that enables the aforementioned actuator characteristics, which in turn enable the development of a high degree-of-freedom anthropomorphic arm. Use of a liquid fuel, however, also brings with it some disadvantages, most notably (1) production of exhaust products, (2) some degree of audible noise associated with the exhaust, (3) elevated internal reaction temperatures, and (4) increased difficulty in packaging relative to a solid energy source such as a battery. Due to the inherently safe nature of the propellant (in concentrations less than 80%), in combination with proper design attention, these issues can be rendered inconsequential. Specifically, with regard to the safety of the propellant, hydrogen peroxide at the proposed concentration levels (70-80%) is completely nonflammable, insensitive to shock, has no possibility of detonation, and has completely safe reaction products (oxygen and steam). Despite this, the propellant is a strong oxidizer, and as such is best distributed in sealed cartridges for consumer distribution, much like CO_2 or propane. Regarding the gas temperature, though clearly elevated internally, the temperature is as low as can be achieved for a given energetic output, and is well within an acceptable range once exhausted from the actuators. With regard to the exhaust temperature, though the adiabatic reaction temperature (i.e., the temperature prior to any extraction of work or heat loss) at the catalyst pack is relatively high (230 C for 70% peroxide), the gas temperature is quickly cooled as it expands through the actuator and performs work. Though the exact exhaust temperature depends on the motion and load, all prior experimental experience (with many types of loads and motions) indicates the exhaust temperature is comfortable for prolonged human exposure (i.e., one can hold one's hand one inch from the exhaust outlet continuously during operation). With regard to the audible output, the sound level of an elbow actuator curling an 11 kg (25 lb) weight at one Hertz was measured at 55 dB from one meter away (which is considered ambient), without any attempt to muffle or attenuate the sound. Thus, with a presumably lower power output, and with minor attempts to muffle the sound, the audible output will likely be below ambient levels (i.e., below 50 dB from one meter).

These characteristics enable the development of an anthropomorphic prosthetic arm with human-like capabilities. The following sections describe the design of such an arm.

III. FOREARM DESIGN

The first important aspect of the design is sizing the pneumatic-type actuators to deliver the requisite human-like performance. The first prototype forearm is designed to deliver 50% of the output capabilities of an unaffected subject's arm. The actuator for a given prosthetic joint is chosen based on the output energy of its anatomical counterpart, which is defined by:

$$E = \tau\theta \tag{1}$$

where τ is the torque applied to the joint and θ is the angular range of motion of the joint. Once the required energy for a given joint is determined, the volume of the pneumatic-type actuator is then determined by:

$$V = \frac{E}{P_s} \tag{2}$$

where P_s is the supply pressure of the working gas and V is the volume of the actuator. The supply pressure for the intial prosthesis prototype is 2.1 MPa (300 psi). For elbow flexion/extension, wrist flexion/extension, and wrist abduction/adduction, an external load of 44.5 N (10 lb) was chosen to represent approximately 50% of the typical human arm load. The joint torque was then computed from the product of the external load and the joint's respective lever arm (35.5 cm for the elbow and 10.1 cm for the wrist joints). With regard to pronation/supination, the anatomical wrist was estimated to provide a torque of 4.2 Nm, as empirically determined from actuation tests of an average unaffected human subject rotating an inertial load in the presence of gravitational acceleration. Table 1 summarizes the requirements for the elbow and three wrist degrees-of-freedom.

Once the required volume for a given actuator is computed, the bore and stroke of the actuator can then be determined based on the required range-of-motion, the linkage design, and the constraint that the prosthesis design should fit within the anatomical envelope of the human arm. Though the volume of the overall prosthesis was a consideration, the predominant constraint with respect to the forearm design was fitting the actuators within the available forearm length. As such, each actuator was chosen to provide the requisite energy with the smallest overall actuator length (stroke plus additional length due to endcaps/ports). Table 2 summarizes the specifications of the actuators chosen for the prosthesis forearm.

TABLE 1
FOREARM REQUIREMENTS

DOF	TORQUE (N-M)	ROM (°)	ENERGY (J)	REQUIRED ACTUATOR VOLUME (M^3)
Elbow Flex/Ext	15.8	160	44.2	$2.1*10^{-5}$
Wrist Flex/Ext	4.5	170	13.4	$6.5*10^{-6}$
Wrist Abd/Add	4.5	60	4.73	$2.3*10^{-6}$
Wrist Pro/Sup	4.2	150	11.1	$5.3*10^{-6}$

TABLE 2
FOREARM ACTUATOR SPECIFICATIONS

DOF	STROKE (CM)	BORE (CM)	MASS (KG)	ACTUAL ACTUATOR VOLUME (M^3)
Elbow Flex/Ext	7.6	1.9	0.12	$2.2*10^{-5}$
Wrist Flex/Ext	5.1	1.4	0.060	$7.8*10^{-6}$
Wrist Abd/Add	2.5	1.4	0.050	$3.8*10^{-6}$
Wrist Pro/Sup	3.8	1.4	0.055	$5.8*10^{-6}$

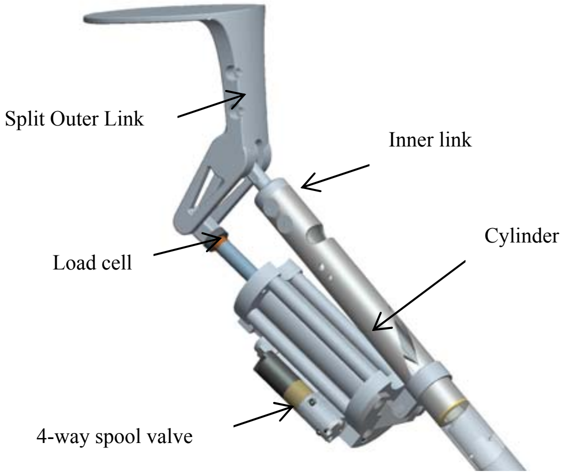

Fig. 2. Solid model of elbow joint.

Fig. 2 depicts a solid model of the elbow joint designed for the anthropomorphic arm. The elbow joint consists of a revolute joint actuated with a flat cylinder (Bimba model FO-043-3V) with a force sensor (Measurement Specialties model ELFS-T4E-100L) integrated in series with the cylinder piston rod. A custom fabricated four-way valve connects to the cylinder ports in order to control the flow of gas to and from the opposing cylinder ports. The revolute joint is composed of an inner link sandwiched between split outer links and incorporates an encoder (HD Systems model MES-6-360PC) for angular position sensing. The encoder body is housed within the inner elbow link with its shaft set-screwed to one of the split outer links. The resulting design provides a range of motion of 105° with hard stops integrated within the split outer links of the revolute joint.

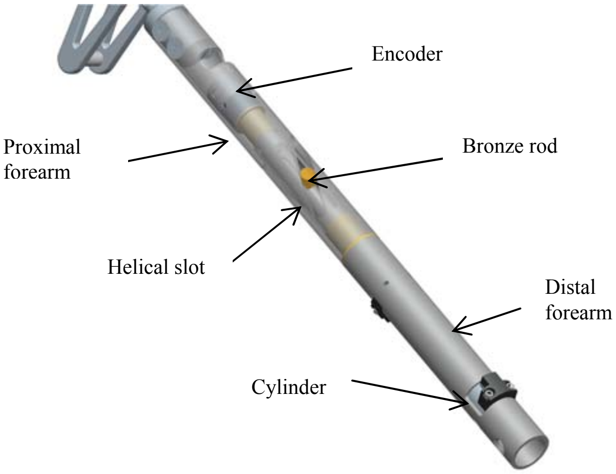

Fig. 3. Solid model of wrist pronation/supination.

Pronation/supination of the wrist is actuated using a variant of a leadscrew assembly, the design of which is shown in Fig. 3. The proximal forearm houses an encoder (HD Systems model MES-6-360PC) to measure angular rotation and includes a helical slot which acts as the leadscrew in the design. The distal forearm houses a non-rotating cylinder (Bimba model NR-021.5-DXPV) and includes a straight slot collinear with the helical slot of the proximal forearm. A custom cylindrical torque sensor is connected in series with the cylinder piston rod, and an orthogonally positioned bronze rod provides for relative rotation of the proximal/distal forearms. As the square-end cylinder rod is displaced, the bronze rod slides within the helical/straight slots of the proximal/distal forearm resulting in rotation of the distal forearm relative to its proximal counterpart with a total range of motion of 115°.

Flexion/extension and abduction/adduction of the wrist, shown in the solid model of Fig. 4, is achieved with a pair of cantilevered revolute joints actuated with a pair of cylinders (Bimba models 022-DXPV and 021-DXPV). Each cylinder includes a load cell (Measurement Specialties model ELFS-T4E-100L) in series with its piston rod for force sensing in each joint. The flexion/extension cylinder has simple pinned joints at each end, but due to coupling in the cantilevered joint pair, the abduction/adduction cylinder must have spherical joints at each end. The cantilevered joint pair integrates encoders (HD Systems model MES-6-360PC) for angular position sensing in each joint. The resulting design provides a range of motion of 95° for wrist flexion/extension and 60° for wrist abduction/adduction.

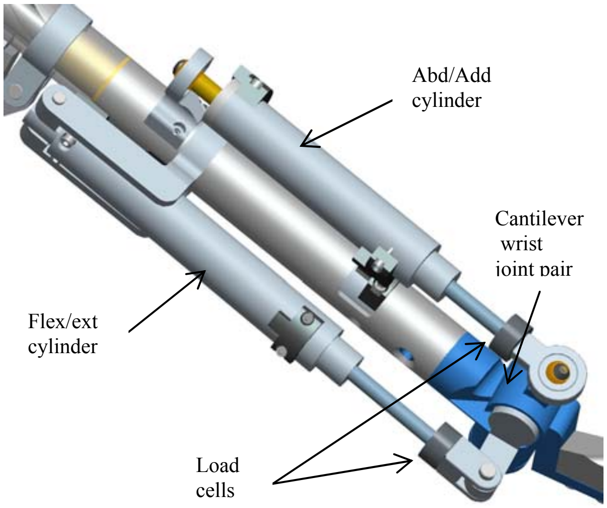

Fig. 4. Solid model of wrist flexion/extension and abduction/adduction.

IV. HAND DESIGN

The anthropomorphic hand for the transhumeral prostheses has 17 coupled degrees-of-freedom driven by five degrees of actuation (Fig. 5). Pneumatic-type actuators for the hand reside in the proximal forearm, similar to native human anatomy. Fig. 6 shows a solid model of the hand cylinders mounted on the distal forearm. The hand cylinders, together with the cylinders for wrist flexion/extension and abduction/adduction, form a group seven actuators positioned radially around and mounted to the distal forearm. The actuator forces are applied through a series of cables and cable sheaths, which are equivalent to the tendons of this hand system. The pneumatic-type cylinders for the hand (Bimba model 0071.5-DV) are equipped with load cells (Measurement Specialties model ELFM-T2E-025L) to measure cable tension. Each actuator delivers 100N (23lbs) of force over a 4cm (1.5in) stroke when operated at the system supply pressure (2.1MPa),. The pneumatic-type cylinders are sized such that the force, power, and energy delivered by each is on the order of 50% of the average anatomical grip capabilities.

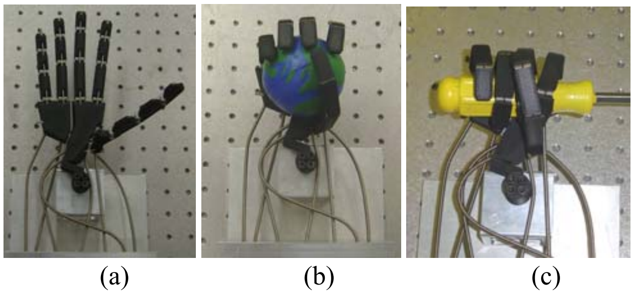

Fig. 5. (a) An ABS prototype of the 17 degree-of-freedom hand fully extended with the use of torsional springs. (b) This prototype demonstrating a spherical grasp. (c) This prototype demonstrating a cylindrical tool grip.

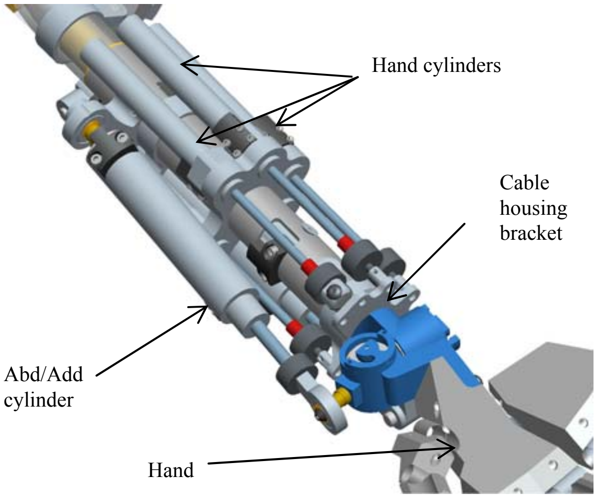

Fig. 6. Solid model of hand cylinders mounted to the distal forearm.

The pneumatic-type actuators are split with one degree for flexion of the first finger, a second for flexion of the second finger, the third for flexion of the thumb, the fourth for the combined flexion of the third and forth fingers through a linear differential, and the last degree of actuation is the coupled link between thumb abduction and palm flexion, or cupping, through a second differential. To provide the anatomic similarity of antagonistic muscles forces within each degree-of-freedom, the hand has two counter wound 8mm diameter, 302 stainless steel torsional springs which provide an extension force to passively oppose the actuator forces. A static hand simulator, shown with a several hand protoypes in Fig. 7, was fabricated to reproduce the five linear actuator motions for assessment of hand kinematics and grasp taxonomy.

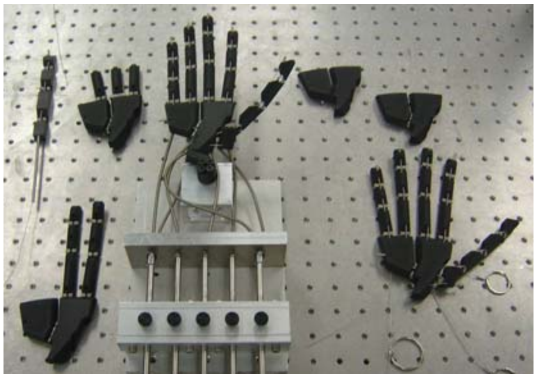

Fig. 7. First three design generations for the hand with the most recent hand placed in the static hand simulator. The simulator was constructed to emulate the actuation of the pneumatic-type actuators

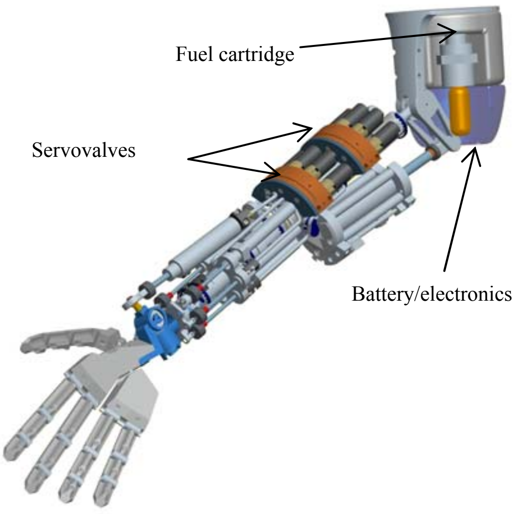

Fig. 8. Solid model of the full arm prosthesis.

V. ANTHROPOMORPHIC ARM PROSTHESIS DESIGN SUMMARY

The full transhumeral prosthesis, shown in Fig. 8, incorporates the forearm and hand designs, along with nine serovalves, hot-gas delivery lines, a fuel cartridge, and on-board power/electronics. The prosthesis has a total of 21 degrees-of-freedom and 9 degrees-of-actuation, with the hand encompassing 17 degrees-of-freedom and 5 degrees-of-actuation. The fuel cartridge carries 200 mL of hydrogen peroxide, which provides 100 kJ based on 70% concentration. A volume of 105 mL is allocated for electronics and a battery for powering sensors and controlling the servovalves. The arm is projected to weigh 15.6 N (3.5 lb), which includes the weight of all components sans the fuel cartridge and electronics, and will deliver approximately 50% of the force, power, and energy of an anatomical human arm.

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