Development of a Hot Gas Actuator for Self-Powered Robots

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Abstract
This paper describes the design of a liquid-propellant-powered hot-gas actuator appropriate for human-scale power-autonomous robots. A prototype of the actuation system is described, and closed-loop tracking data is shown that demonstrates good motion control. Experiments to characterize the energetic performance of the actuation system indicate that the proposed system with a diluted propellant offers an energetic figure of merit five times greater than a battery-powered DC motor actuated system. Projections based on these experiments indicate that the same system powered by undiluted propellant would offer an energetic figure of merit an order of magnitude greater than battery-powered DC motor actuated systems.

1 Introduction
1.1 Motivation
One of the most significant challenges in the development of an autonomous human-scale robot is the issue of power supply. Perhaps the most likely power supply/actuator candidate system for a position or force actuated human-scale robot is an electrochemical battery and DC motor combination. This type of system, however, would have to carry an inordinate amount of battery weight in order to perform a significant amount of work for a significant period of time. A state-of-the-art example of a human-scale robot that utilizes electrochemical batteries combined with DC motor/harmonic drive actuators is the Honda Motor Corporation humanoid robot model P3. The P3 robot has a total mass of 130 kg (285 lb), 30 kg (66 lbs) of which are nickel-zinc batteries. These 30 kg of batteries provide sufficient power for approximately 15-25 minutes of operation, depending on its workload. Operation times of this magnitude are common in self-powered mobile robots that can operate power-autonomously for extended periods of time.

1.2 Figure of Merit
Assuming that a given power supply and actuation system can deliver the requisite average and peak output power at a bandwidth required by a power-autonomous robot, three parameters are of primary interest in providing optimal energetic performance. These are the mass-specific energy density of the power source, $e_u$, the efficiency of converting energy from the power source to controlled mechanical work, $\eta$, and the maximum mass-specific power density of the energy conversion and/or actuation system, $p_a$. A simple performance index is constructed by forming the product of these parameters,

$$A_p = e_u \eta p_a$$

where $A_p$ is called the actuation potential. In the case of a battery-powered DC-motor-actuated robot, the energy density of the power source $e_u$ would be the electrical energy density of the battery, the conversion efficiency $\eta$ would be the combined efficiency of the (closed-loop controlled) DC motor and gearhead, and the power density of the energy conversion and actuation system $p_a$ would be the rated output power of the motor/gearhead divided by its mass. In the case of a gasoline-engine-powered hydraulically-actuated system, the energy density of the power source would be the thermodynamic energy density of gasoline; the conversion efficiency would be the combined efficiency of the internal combustion engine (converting thermodynamic energy to shaft energy), hydraulic pump (converting shaft energy to hydraulic energy), and the hydraulic actuation system (converting hydraulic energy to controlled mechanical work); and finally, the power density of the energy conversion and actuation system would be the maximum output power of the hydraulic actuation system, divided by the combined mass of the engine, pump, accumulator, valves, cylinders, reservoir, and hydraulic fluid of the hydraulic system. With regard to this figure of merit, batteries and DC motors capable of providing the requisite power for a human-scale robot offer a reasonable conversion efficiency, but provide relatively low power source energy density and a similarly low actuator/gearhead power density. A gasoline-engine-powered hydraulically-actuated human-scale robot would provide a high power source energy density, but a relatively low conversion efficiency and actuation system power density.

1.3 A Monopropellant Powered Approach
Liquid chemical fuels can provide energy densities significantly greater than power-comparable electrochemical batteries. The energy from these fuels, however, is released as heat, and the systems required to convert heat into controlled, actuated work are typically complex, heavy, and inefficient. One means of converting chemical energy into controlled, actuated work with a simple conversion process is to utilize a liquid monopropellant to generate a gas, which in turn can be utilized to power a pneumatic actuation system. Specifically, monopropellants are a class of fuels (technically propellants since...
oxidation doesn’t occur) that rapidly decompose (or chemically react) in the presence of a catalytic material. Unlike combustion reactions, no ignition is required, and therefore the release of power can be controlled continuously and proportionally simply by controlling the flow rate of the liquid propellant. This results in a simple, low weight energy converter system, which provides a good solution to the design trade-offs between fuel energy density and system weight for the scale of interest.

Modern day applications of monopropellants include torpedo propulsion, reaction control thrusters on a multitude of space vehicles, and auxiliary power turbo pumps for aerospace vehicles. Despite the use of monopropellants in these various applications, the authors have not been able to find any prior literature describing the development of position or force controllable monopropellant-powered actuators. The only indication of prior related work is the patent by Morash [1], which describes a pilot-operated binary valve that utilizes a monopropellant in the pilot stream. The work reported here describes the design of a monopropellant-powered actuation system appropriate for human-scale self-powered robots, and presents experimental results that indicate the strong potential of this system for high energy density human-scale robot applications.

2 Monopropellant Actuation System
A schematic drawing of the proposed actuation system is shown in Fig. 1. The conversion of stored chemical energy to controlled mechanical work takes place as follows. The liquid $\text{H}_2\text{O}_2$ is stored in a tank pressurized with inert gas (called a blowdown tank) and metered through a catalyst pack by a solenoid-actuated control valve. Upon contact with the catalyst, the peroxide expands into oxygen gas and steam. The flow of peroxide is controlled to maintain a constant pressure in the reservoir, from which the gaseous products are then metered through a voice-coil-actuated 4-way proportional spool valve to the actuator. Once the gas has exerted work on its environment, the lower energy hot gas mixture is exhausted to atmosphere.

3 Monopropellant Actuator Prototype
3.1 Hardware
A prototype of the monopropellant-powered actuation system depicted in Fig. 1 was fabricated and integrated into a single degree-of-freedom manipulator, as shown in Fig. 2. The primary objective of building the prototype was to demonstrate tracking control and to conduct experiments characterizing the actuation potential described by (1). The propellant is stored in a stainless steel blow-down propellant tank, and is metered through a 2-way solenoid-actuated fuel valve (Parker/General Valve Series 9) through a catalyst pack and into a stainless steel reservoir. The catalyst pack was constructed in-house and consists essentially of a 5 cm (2 in) long, 1.25 cm (0.5 in) diameter stainless steel tube packed with catalyst material. A pressure sensor (Kulite model XTME-190-250A) measures the reservoir pressure for purposes of pressure regulation. The high pressure hot gas is metered into and out of a 2.7 cm (1-1/16 in) inner diameter, 10 cm (3.9 in) stroke double-acting single-rod cylinder (Bimba model 094-DX) by a 4-way spool valve (Numatics Microair model #M11SA441M), modified for proportional operation by replacing the solenoid actuator with a thermally isolated voice coil (BEI model #LA09-10-000A). The valve spool displacement is measured with a DVRT (Microstrain model #2247-6) in order to enable closed-loop control of the valve spool position. The pneumatic cylinder is kinematically arranged to produce a bicep curling motion upon extension of the piston, as illustrated in Fig. 3.

Fig. 1. Schematic of monopropellant actuation system.

Fig. 2. Single degree-of-freedom manipulator with monopropellant-based actuation prototype.

3.2 Control
Control of the system is achieved using three separate control loops. The first and simplest is the pressure regulation of the reservoir. Pressure feedback from the pressure sensor switches the solenoid fuel valve with a thermostat-type on-off controller that regulates the reservoir.
pressure to 1515 kPa (220 psig). The second control loop provides high bandwidth (i.e., approximately 10 Hz) position control of the valve spool. Specifically, the DVRT provides position feedback for a PID controller with feed-forward Coulomb friction compensation that positions the spool by means of the voice coil actuator. Finally, the valve spool position is commanded by an outer control loop, which controls the angular motion of the single degree-of-freedom manipulator. The outer control loop utilizes a rotary potentiometer to provide arm angle measurement for a PVA (position, velocity, acceleration) feedback controller, which as previously mentioned commands the valve spool position. These control loops were all implemented at a sampling rate of 1 kHz with the real-time interface provided by MATLAB/Simulink (The MathWorks, Inc.). Tracking performance of the manipulator is demonstrated by the data shown in Figs. 4 and 5, both of which reflect tracking with an 11 kg (25 lb) endpoint mass (as shown in Fig. 2) and 70% hydrogen peroxide solution (i.e., diluted with 30% water by weight). Specifically, Fig. 4 shows 30-degree amplitude, 1 Hz sine wave tracking, and Fig. 5 shows tracking of an arbitrary input, which was generated by measuring human elbow motion with a goniometer.

$$T = ml\ddot{\theta} + mg\sin \theta.$$  
(2)

The instantaneous power could then be calculated as:

$$P(t) = |\dot{\theta}|,$$  
(3)

where the absolute value operator reflects the fact that typical spool-valve controlled systems are energetically non-conservative. The average power was calculated by integrating over an integer number of cycles $n$,

$$P_{\text{ave}} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} P(t) dt$$  
(4)

where $\omega(t_1 - t_1) = 2\pi n$. The propellant mass consumption was measured indirectly by recording the pressure of the nitrogen gas in the blowdown tank, assuming an isothermal process inside the constant-volume tank, and calculating the volume occupied by the nitrogen from the ideal gas equation, which in turn yields the volume of propellant in the tank. Since the propellant is a liquid, the mass of propellant used, $m_{p_{\text{prop}}}$, is easily computed from the known volume and density. The conversion efficiency is then computed over an integer number of cycles as follows,

![Fig. 3. Kinematic diagram of manipulator.](image)

![Fig. 4. Closed-loop tracking control of a 30-degree amplitude 1 Hz sinusoid. The dashed line is the commanded input and the solid is the manipulator motion.](image)

![Fig. 5. Closed-loop tracking control of arbitrary human movement. The dashed line is the commanded input and the solid is the manipulator motion.](image)

### 4 Energetics

Experiments were conducted to measure the actuation potential as given by (1). In these experiments, a 70% peroxide solution was used as the propellant to maintain acceptable temperatures for commercially available components. The single degree-of-freedom manipulator was commanded to move the 11 kg mass through a 30-degree amplitude, 1 Hz sinusoidal motion enveloped by initial and final angles of $\theta_1 = 38$ degrees and $\theta_2 = 98$ degrees, respectively, defined relative to the downward vertical as depicted in Fig. 3. The work output was computed indirectly by measuring the angle and, in post-processing, computing the actuation torque using a model of the load, given by:

$$T = ml\ddot{\theta} + mg\sin \theta.$$  
(2)
\[ \eta = \frac{P}{e_S m} \]  

(5)

where \( e_S \) is again the heat of decomposition of 70% hydrogen peroxide solution. Based on these measurements, the experimentally determined conversion efficiency was found to be \( \eta = 6.6\% \). Note that the electrical power required to operate the valves was neglected in this analysis. The measured average combined electrical power required by the fuel and gas valves was approximately 2 W. Since this is only about 3% of the average work delivered by the actuator, this electrical power can be legitimately omitted from the analysis. A thermodynamic model developed by the authors indicated that the expected upper bound on the efficiency for these experiments would be 16%. The significant discrepancy between the measured conversion efficiency of 6.6% and the calculated upper bound of 16% is due to two major factors. The first is inefficiency in control and the second is heat loss. Specifically, the thermodynamic model assumed that no gas was exhausted during a given monotonic segment of the trajectory, and that no energy was lost as heat. Regarding the former, any overshoot of the desired trajectory will violate the assumed monotonicity of the trajectory, and therefore will result in an intermittent exhaust of hot gas and a resulting decrease in the efficiency. The existence of such intermittent exhaust is evident in the oscillations exhibited in the power delivered to the load, computed from (2-3), which is shown in Fig. 6 plotted against the theoretically required power. Regarding inefficiency due to heat loss, the external surfaces of the catalyst pack, reservoir, and actuator were hot during the experiments, thus indicating the presence of heat flow. In order to more quantitatively assess the degree of heat loss, the prototype was instrumented with thermocouples so that the rate of heat loss could be estimated from surface temperature measurements referenced to tables associated with heat loss from uninsulated steam piping [5]. This measurement yielded an estimated heat loss rate of 140 W. Note that the average measured mechanical power output was approximately 60 W. The prototype lost twice as much energy in the form of heat as it delivered in the form of work. The decrease in efficiency due to heat loss was accounted for in the thermodynamic model developed by the authors. For the experimental conditions described by Table I, and with an average heat loss rate of 140 W, the conversion efficiency was recalculated to be \( \eta = 10.0\% \), as compared to the measured value of \( \eta = 6.6\% \). Having accounted for the heat loss, the remaining discrepancy is presumably due to the closed-loop control inefficiency, which is not so easily accounted for in the thermodynamic model.

In order to improve the measured conversion efficiency, the catalyst pack, reservoir, and actuator were wrapped in insulating tape, as shown in Fig. 7, and measurement of the conversion efficiency was repeated. For the insulated case, the experimentally determined conversion efficiency was found to be \( \eta = 9.0\% \). Thermocouple measurement of the surface temperatures, as previously described, yielded an estimated heat loss rate of 73 W, approximately half of the uninsulated case. Using this heat loss rate, the theoretically calculated efficiency was \( \eta = 12.0\% \), the difference presumably due to control inefficiency (i.e., intermittent exhausts).

Fig. 6. A comparison of the measured power delivered by the actuator (solid) to the theoretically predicted power (dashed) required to track the specified angular trajectory of the arm. Also shown is the estimated peak power (also dashed).

Fig. 7. Monopropellant actuator prototype wrapped with insulating tape and instrumented with thermocouples for measurement of surface temperature.
Having determined the actuator power density, only the power source energy density need be found in order to calculate the actuator potential. As previously mentioned, the heat of decomposition of 70% hydrogen peroxide propellant is 2.0 MJ/kg. The propellant must be stored, however, in a pressurized blowdown propellant tank, and as such a legitimate characterization of the energy density should include the mass of a tank. Based on available data for a composite overwrapped propellant tank [6], the mass of a propellant tank for a volume on the order of 10 liters would conservatively decrease the mass-specific energy density of 70% peroxide from approximately 2.0 MJ/kg to approximately 1.7 MJ/kg. Based on this and the measured values of conversion efficiency and actuator power density previously described, the actuation potential for this single degree-of-freedom system, as given by (1), would be $A_p = 15.3 \text{ kJ-kW/kg}$. As previously mentioned, the power density will increase for a multi-degree-of-freedom system, and thus so will the actuation potential. For a six degree-of-freedom system, for example, the total actuation system mass would be 5.2 kg, or 870 g per actuator. Note that the reservoir used in the single degree-of-freedom experiment was oversized, and is appropriately sized for a power-comparable six degree-of-freedom system. The actuation system power density would therefore increase to $p_a = 172 \text{ W/kg}$, and the corresponding actuation potential to $A_p = 26.4 \text{ kJ-kW/kg}^2$ for the six degree-of-freedom system.

For purposes of comparison, the best commercially available rechargeable batteries have energy densities of approximately 180 kJ/kg (e.g., Evercel M40-12 nickel zinc, or SAFT 27x10 LAS silver zinc). A rare-earth permanent-magnet DC motor with a harmonic drive gearhead with output characteristics capable of achieving the trajectory specified by Table I, has a power density of approximately 48 W/kg (e.g., Kollmorgen model N12M4 Neodymium Servodisc motor with Harmonic Drive Technologies PSS-G20-100 gearhead). Note that this remains invariant, regardless of the number of degrees of freedom. Finally, one can assume that the overall conversion efficiency would be the combined efficiencies due to PWM control, the motor, and the gearhead. The PWM efficiency was estimated to be 95%, the motor efficiency calculated for the desired trajectory to be 90% (i.e., the resistive power loss in the motor windings was calculated given the desired torque), and the harmonic drive gearhead efficiency was estimated based on manufacturer data to be 65%. The resulting actuation potential for this type

### Table I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Pressure in tank ($P_i$)</td>
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<tr>
<td>Temperature in tank ($T_i$)</td>
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<tr>
<td>Mass fraction ($\alpha$)</td>
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<tr>
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<tr>
<td>Final angle ($\theta_f$)</td>
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<td>Load mass ($m$)</td>
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<td>Arm length ($l$)</td>
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<tr>
<td>Arm geometry: $d_1$</td>
<td>5.6 cm</td>
</tr>
<tr>
<td>Arm geometry: $d_2$</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Arm geometry: $d_3$</td>
<td>27 cm</td>
</tr>
<tr>
<td>Arm geometry: $d_4$</td>
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### Table II

<table>
<thead>
<tr>
<th>Actuation Component</th>
<th>Mass (g)</th>
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</thead>
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<tr>
<td>Proportional spool valve</td>
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<td>Pressure sensor</td>
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<tr>
<td>Fuel valve</td>
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<tr>
<td>Catalyst pack</td>
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<tr>
<td>Reservoir tank</td>
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<tr>
<td>Pneumatic cylinder</td>
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</tr>
<tr>
<td>Fittings</td>
<td>300</td>
</tr>
<tr>
<td><strong>TOTAL ACTUATOR</strong></td>
<td><strong>1500</strong></td>
</tr>
</tbody>
</table>

4.1 Experimentally determined actuation potential

Having measured the conversion efficiency, the mass-specific power density of the actuator and the mass-specific energy density of the power source need to be determined in order to calculate the actuation potential given by (1). The former is found by determining the mass and the maximum output power of the energy conversion and actuation system. Though finding the mass is a trivial task, characterizing the maximum deliverable power is not as straightforward, in large part due to the dependence upon several factors, including the supply pressure, the valve flow coefficient ($C_v$) of the proportional valve, and the nature of the load, among others. In order to base the actuator power density solely on measured data, the authors chose to conservatively estimate the maximum deliverable power by using the peak power consistently measured during the previously described efficiency experiments. As evidenced by the data in Fig. 6, the actuator can consistently generate 150 W, as indicated by the dashed line overlaid on the plot. The mass of the actuation system was obtained by weighing the components of the actuator shown in Fig. 2. The mass of each component is summarized in Table II. As indicated in the Table, the total actuation system mass is 1.5 kg, thus resulting in an actuation system power density of $p_a = 100$ W/kg. This would increase for a multi-degree-of-freedom system, since such a system would only include a single fuel valve, catalyst pack, pressure reservoir, and pressure sensor.
of system would therefore be $A_p = 4.8 \text{ kJ-kW/kg}^2$. The poorly insulated single-degree-of-freedom experimental setup with 70% peroxide therefore exhibited an actuation potential more than three times a state-of-the-art battery/DC motor system. A similar six degree-of-freedom system would exhibit an actuation potential over fives times the battery/DC motor system.

4.2 Projected performance for high-test propellant
Though improvements can clearly be made with improved insulation and control performance, the most obvious means of improving the actuation system performance is to substitute a fully concentrated version of the propellant (i.e., 100% hydrogen peroxide) in place of the 70% solution used in the previously described experiments. Though procedurally quite simple, such experiments cannot be performed on commercially available pneumatic components, due to the high decomposition temperatures. Specifically, the adiabatic decomposition temperature of 100% peroxide is approximately 1000°C (1800°F), compared to approximately 230°C (450°F) for a 70% solution. Rather than conducting experiments using 100% peroxide, one can obtain a reasonable estimate of performance with projections based upon the experiments conducted with 70% solution. Upon replacing 70% propellant with 100% (technically 99.6%), at least two of the three parameters forming the actuation potential figure of merit would be expected to increase. Specifically, since the propellant contains more peroxide per unit mass, the heat of decomposition increases by a factor of 1.46 from 1.98 MJ/kg to 2.88 MJ/kg. Additionally, recall that the relatively low experimentally determined conversion efficiencies were primarily due to the heat required to vaporize the water in the reaction product. Since the 100% propellant contains less water, less energy is invested in vaporizing the reaction product. Recalculating the expected efficiencies accounting for the reduced water content, the conversion efficiency scales by a factor of 1.56. Assuming that the actuation system power density remains invariant (i.e., that it does not increase with the 100% propellant), the single degree-of-freedom system shown in Fig. 2 with 100% propellant would be expected to have an actuation potential of $A_p = 35.0 \text{ kJ-kW/kg}^2$, which is 7.3 times greater than the battery/DC motor system. A similar six degree-of-freedom system would exhibit an actuation potential of $A_p = 60.4 \text{ kJ-kW/kg}^2$, more than an order of magnitude greater than the battery/DC motor system. The promise of such performance, which would presumably be further improved with better insulation and lightweight components, justifies the fabrication of custom high-temperature pneumatic components.

5 Conclusions
A power supply and actuation system appropriate for a position or force controlled human-scale robot was proposed. The proposed approach utilizes a monopropellant as a gas generant to power pneumatic-type hot gas actuators. Experiments were performed that characterize the energetic behavior of the proposed system and offer the promise of an order-of-magnitude improvement in actuation potential relative to a battery-powered DC-motor-actuated approach. Experiments also demonstrated good tracking and adequate bandwidth of the proposed actuation concept.

References