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The objective of the proposed work is to develop and demonstrate an actuation system that provides direct chemical to mechanical energy conversion from an energy source that is approximately an order of magnitude more energy dense and power dense than the best commercially available lithium-thionyl-chloride or lithium-manganese-dioxide electrochemical batteries. Specifically, the proposed system utilizes the monopropellant hydrogen peroxide (H_2O_2) to maintain a high-pressure pneumatic reservoir, which is in turn utilized as a controllable power source for a system of pneumatic actuators. A key attribute of the proposed system is its simplicity. The monopropellant produces a low temperature reaction that generates completely benign byproducts. Additionally, the use of pneumatic actuators produces a lightweight system that is well impedance-matched to a human operator. The one-year feasibility study will develop and demonstrate the monopropellant-powered actuator.

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Barth, E.J., Zhang, J., and Goldfarb, M. Performance and Stability Robustness in PWM-Controlled Pneumatic Systems. *ASME Journal of Dynamic Systems, Measurement, and Control*, In review.

Barth E. J., Zhang, J., and Goldfarb, M. A Method for Model-Based Control of Pulse-Width-Modulated (PWM) Pneumatic Systems. *IEEE/ASME Transactions on Mechatronics*, In review.

Gogola, M., Barth, E.J., and Goldfarb, M. Monopropellant-Powered Actuators for use in Autonomous Human-Scale Robotics. Accepted for presentation at the *IEEE International Conference on Robotics and Automation*, May 2002.

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Program Description:

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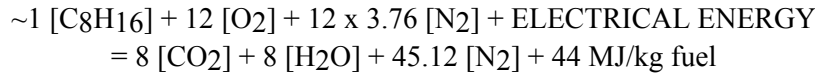
Accomplishments to Date:

- Survey of chemical-to-mechanical energy conversion
- Thermodynamic analysis of energy extraction from monopropellant
- Experimental demonstration of mechanical energy extraction from monopropellant
- Development and characterization of actuator prototype

Survey of Chemical-to-Mechanical Energy Conversion

Three major classes of energetic reactions were considered: combustion, in which a fuel and oxidizer are ignited by an ignition source, hypergolic bipropellants in which a fuel and oxidizer spontaneously ignite upon contact, and monopropellant reactions, in which a single fuel reacts in the presence of a catalyst. Combustion reactions can be divided into air-breathing and non-air-breathing types. The basic structure of the former is as follows:

$$fuel + air + energy = reaction\ products + heat$$
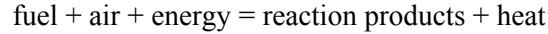
A common example of this type of reaction is gasoline/air combustion, which is given stoichiometrically as follows:

$$\sim 1\ [C_8H_{16}] + 12\ [O_2] + 12 \times 3.76\ [N_2] + ELECTRICAL\ ENERGY$$
$$= 8\ [CO_2] + 8\ [H_2O] + 45.12\ [N_2] + 44\ MJ/kg\ fuel$$

Note that if the weight of the air is included with the weight of the fuel, then this reaction will only produce about 2.8 MJ/kg of fuel and air together. Since air is generally available, hydrocarbon/air combustion provides extremely high fuel-specific energy densities. Since a large volume of air must be compressed in order to react with a small volume of fuel, air breathing requires significant mechanical and energetic overhead. For example, the majority of the size of a turbojet engine is due to the compressors, which are required to feed the engine enough fuel to stoichiometrically react with the jet fuel. These systems additionally require an ignition system, and as such, it is unclear how to develop direct energy conversion actuator from this type of reaction.

Non-air-breathing combustion offers an alternative to air breathing that significantly reduces system complexity (i.e., the need for air breathing apparatus). The basic structure of this type of reaction is as follows:

$$fuel + oxidizer + energy = reaction\ products + heat$$
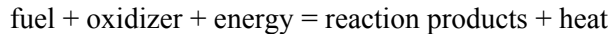
For example, if gasoline is reacted with pure oxygen, the reaction will produce 10 MJ/kg fuel and oxygen. Since pure oxygen is not an easily storable oxidizer, a more realistic example might be gasoline and nitrogen tetroxide (N_2O_4), which will produce approximately 7.5 MJ/kg fuel and oxidizer. This type of reaction does not require any air compression apparatus, but the fuel specific energy density is significantly lower than air breathing combustion. The energy conversion system, however, is much simpler. This type of system still requires an ignition system, and thus it is unclear how to develop a direct energy conversion actuator.

Hypergolic combustion offers an alternative to non-air-breathing combustion that does not require an ignition system. The basic structure of this type of reaction is:

$$fuel + oxidizer = reaction\ products + heat$$

An example is the reaction of hydrazine with nitrogen tetroxide, which is described by:

$$2[N_2H_4] + [N_2O_4] = 4[H_2O] + 3[N_2] + 5\ MJ/kg\ fuel+oxidizer$$
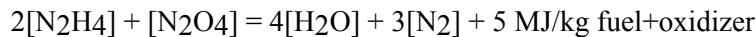
In this type of reaction, no air-breathing apparatus is required and no ignition system is required, and thus this approach is well suited to a direct energy conversion actuator. Use of hypergolic fuels provides a

much lower energy density relative to air-breathing hydrocarbons, but a comparable energy density to non-air-breathing hydrocarbons. Since the fuel and oxidizer must be kept separate, however, storage and mixing of two liquids increases the system complexity and compromises safety.

Finally, a monopropellant type reaction provides energy release with a single fuel. The basic structure of the reaction is:

$$\text{fuel} + \text{catalyst} = \text{reaction products} + \text{heat}$$
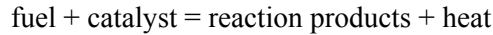
An example of such a reaction is hydrogen peroxide, which is described by:

$$2[H_2O_2] + \text{CATALYTIC SURFACE} = 2[H_2O] + [O_2] + 3 \text{ MJ/kg fuel}$$

In this type of reaction, no air-breathing apparatus is required, no ignition system required, it is well suited to a direct energy conversion actuator, and the system entails the storage and handling of a single fuel. As a result, the system is functionally and structurally much simpler than the other previously described approaches. The energy density, however, is significantly lower relative to air-breathing hydrocarbons and somewhat lower relative to hypergolics. A monopropellant approach, however, offers a much simpler, smaller, and lighter conversion system that is far better suited to human-scale robotics applications.

Thermodynamic analysis of energy extraction from monopropellant

As stated previously, the thermodynamic energy density of H_2O_2 is 2.9 MJ/kg, which is to say that this energy is released as heat. In order to assess the potential of an H_2O_2 powered actuator, a model should be constructed to ascertain what percentage of this energy can be extracted as (instantaneous) mechanical work. The following section describes a model of the energy conversion process.

The monopropellant reactants are assumed to behave as an ideal gas with a constant specific heat undergoing adiabatic expansion. In such a case, the first law of thermodynamics states that the work done by the system will be the same as the decrease in internal energy. The molar specific decrease in internal energy is given by:

$$du = c_v dT$$

where u is the molar specific internal energy, c_v is the specific heat and T is the temperature of the gas. The molar specific work done by the system is:

$$dw = p\,dv$$

where w is the molar specific work, p is the pressure, and v is the molar specific volume. The ideal gas is described by

$$p = \frac{\overline{R}T}{V}$$

where $\overline{R}$ is the universal gas constant. Substituting yields:

$$c_v dT = -\frac{\overline{R}T dv}{v} \quad \text{or} \quad \frac{c_v dT}{T} = -\frac{\overline{R}\, dv}{v}$$

and integrating from conditions A to B :

$$c_v \ln(T_A / T_B) = \overline{R} \ln(v_B / v_A)$$

Substituting the following ideal gas relations

$$\overline{R} = c_p - c_v$$

$$\gamma = \frac{c_p}{c_v}$$

yields the isentropic relationship

$$T_A v_A^{\gamma-1} = T_B v_B^{\gamma-1}$$

Substituting this into the equation for internal energy yields:

$$\Delta u = c_v (T_A - T_B) = c_v T_A (v_{AB}^{\gamma-1} - 1)$$

which can be expressed as:

$$\Delta u = \frac{\overline{R}T_A}{\gamma - 1}(v_{AB}^{\gamma-1} - 1)$$

where

$$v_{AB} = \frac{v_A}{v_B} = \frac{V_A}{V_B}$$

Therefore, the amount of energy converted to mechanical work per gram of fuel

$$w = \frac{\overline{R}T_A}{M(\gamma-1)}(1 - v_{AB}^{\gamma-1})$$

Incorporating this equation and assuming 100% hydrogen peroxide fuel and assuming a volume expansion ration of 0.15, this analysis indicates that the fuel will provide approximately 710 kJ of mechanical energy per kg of peroxide fuel.

Initial experimental demonstration

As shown in Figures 1 and 2, an experimental demonstration was conducted to ascertain the viability of the proposed method. In the demonstration, 70% peroxide fuel pressurized by nitrogen gas to 150 psi. The liquid was valved through a catalyst pack into a pneumatic cylinder, where it deformed a set of mechanical springs. The lower temperature gas was then exhausted through a exhaust valve to atmosphere. The experiment was manually operated, though a computer-controlled version is described in the following section.
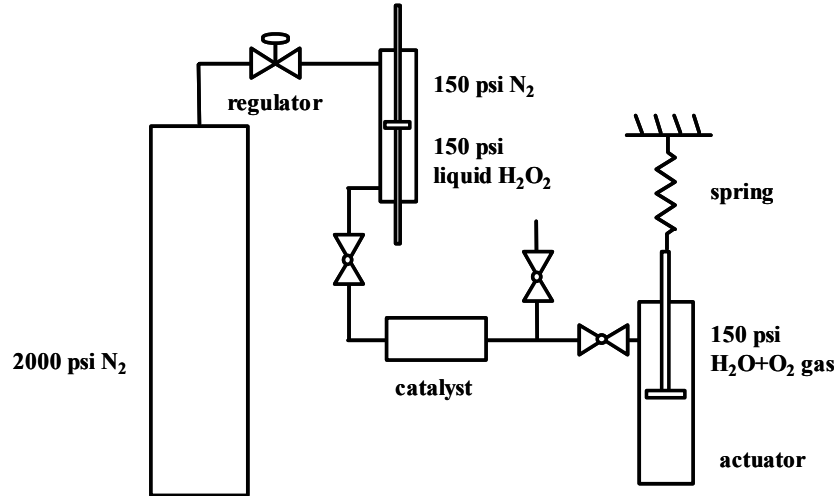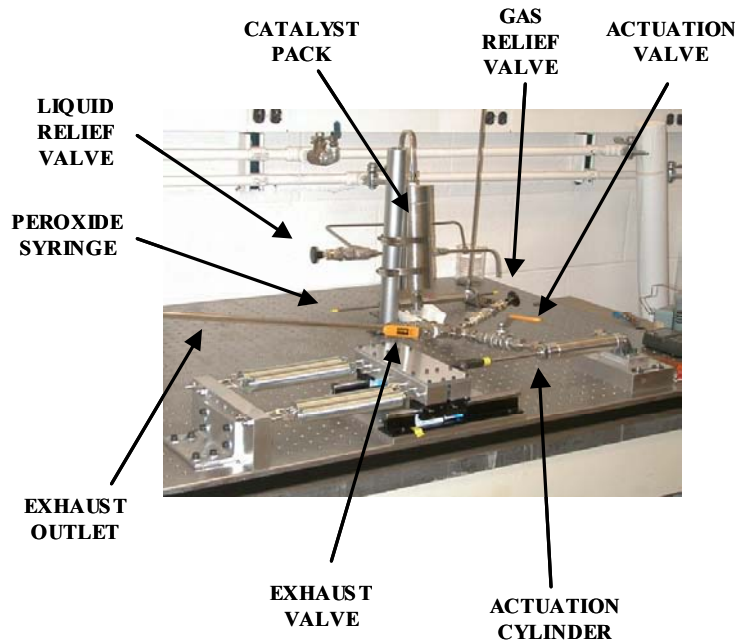

Figure 1. Schematic of experimental setup.

Figure 2. Experimental setup for monopropellant demonstration.

Description of the Monopropellant Actuation System

A conceptual drawing of the proposed actuation system is shown in Figure 3. The monopropellant-powered actuation system is similar in several respects to a typical pneumatically actuated system, but rather than utilize an electric-motor-driven or internal-combustion-engine-driven compressor to maintain a high-pressure reservoir, the proposed system utilizes the direct expansion of a hydrogen peroxide (H_2O_2) monopropellant into the reservoir. Specifically, though H_2O_2 is generally stable in air, the liquid is highly unstable in the presence of a catalyst, and as a result expands rapidly into humidified oxygen gas. The exact composition of the reaction product is 33% oxygen by volume and 67% water vapor by volume. Heat released from this rapid decomposition of the fuel heats the gas products and provides the thermal energy from which mechanical work can be extracted.
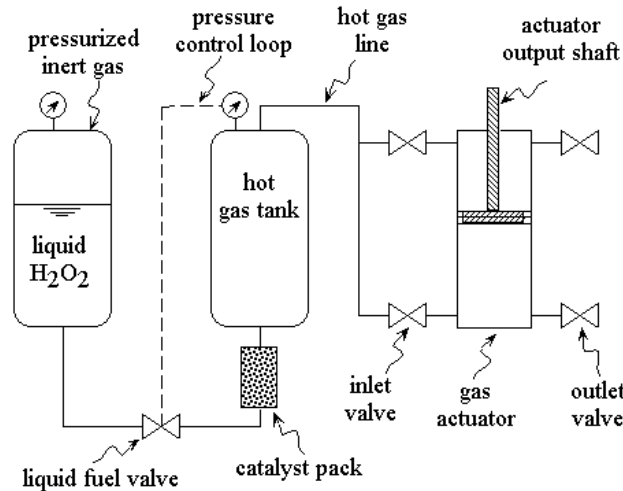

Figure 3. Schematic of monopropellant-based actuation system

The proposed system is implemented by storing the liquid H_2O_2 in a pressurized tank and releasing it through a controlled valve, which meters the liquid H_2O_2 through a catalyst, at which point the peroxide quickly (relative to robot dynamics) expands into oxygen gas containing water vapor. The decomposition of peroxide is controlled to maintain a constant supply pressure in the reservoir, from which the gaseous products are then metered through proportional valves to the actuators. Once the gas has exerted work on its environment, the lower energy oxygen vapor is exhausted to atmosphere, so (unlike a hydraulic system), no return path for the fluid is necessary.

A key attribute of the proposed system is its simplicity. Use of the H_2O_2 monopropellant to regulate the pressure in a pneumatic reservoir requires only a pressurized tank of liquid H_2O_2, a binary solenoid fuel valve (i.e., non-proportional), a catalyst bed, and a pressure sensor in the reservoir. Unlike the combustion of hydrocarbon fuels, this approach does not require premixing, precompression, a cooling system, or an ignition system. The actuation system provides centralized power, so that weight, bulk, and inertia at the extremities are minimized. Minimal weight and inertia minimizes the amount of actuator torque and energy expended on acceleration and deceleration of limb segments (assuming non-recoverable energy, as are all actuators under closed-loop control), and decreases the awkwardness of the robot due to excessive bulk. Finally, the rapid decomposition of H_2O_2 is a quiet reaction, and when enclosed in a pneumatic reservoir, is essentially silent.

System Comparison

A study was performed to determine the feasibility of a human scale monopropellant robotic system as compared to that of a more conventional DC motor-based approach. For this study, a two-legged walking robot design was investigated. A design using six actuators was assumed, one for each hip, knee, and

ankle joint. The total system mass was set at 90 kg, with 40 kg devoted to payload/structural mass and the other 50 kg devoted to the actuator system. The actuator system weight was comprised of fuel, the weight of the actuators, and the weight of any equipment required to transfer the energy from the power source to the actuators (i.e. valves, gearhead, etc.). Three separate systems were investigated; a battery powered DC motor with gearhead actuator system, a 70% concentration H_2O_2 monopropellant-powered pneumatic actuation system, and a 100% concentration H_2O_2 monopropellant-powered pneumatic actuation system. Note that the intermediate case (70% H_2O_2) was only computed for comparison to current experimental results, and normally would not be implemented in a target system.

In sizing the components for the 90 kg robotic system, the torque, speed, and power requirements for each joint were approximated by using existing mass specific biomechanical data for human gait [1]. Table 1 shows the normalized average and peak power required from each sagittal plane lower limb joint during an average walking speed of 3.5 mph. Table 1 also shows the scaled average and instantaneous power required for a 90 kg walking device. Actuators were sized to handle the required peak power, torque, and speed for each joint, and selected using commercially available components. Additionally, all power was assumed to be non-recoverable (i.e., the control system had no regenerative ability). Further, the cost of controlling the instantaneous power exerted by the actuator was assumed to add to the overall energetic cost of the system.

To compare the performance of each system, the power density and energy density were computed. The power density is the maximum deliverable mechanical power of the system normalized by the total system weight. Likewise, the system energy density is the amount of stored energy in the system that can be transformed into mechanical work, normalized by the total system weight. Both values include adjustments for component efficiencies based on assumptions of their abilities to transfer the energy from the power source to the actuators.

Table 1. Normalized and scaled joint power requirements for a normal walking cadence at 3.5 mph [1].

Joint	Hip	Knee	Ankle
Normalized average power (W/kg)	0.163	0.270	0.517
Normalized peak power (W/kg)	0.66	0.86	4.5
Scaled average power (W)	14.7	24.3	46.5
Scaled peak power (W)	59.4	77.4	405

In addition, two other significant values were computed for each system. These are the maximum power density of the system and the maximum energy density of the system. These values are theoretical abstractions and are given as boundary conditions on the capabilities of system performance. They represent the extremes of scaling the system.

The maximum power density is limited by some component of the actuation system. The system will obtain maximum power density when the mass of the fuel is negligible relative to the mass of the actuator system, or when the mass of the fuel is approximately one tenth (or less) of the actuation system mass. A system will obtain its maximum energy density in the other extreme, when the actuator system mass is negligible relative to the fuel mass, which will occur when the fuel mass is approximately ten times (or more) the actuation system mass. The maximum energy density and power density will therefore, in general, not be simultaneously obtainable in any system.

Battery powered DC motor with gearhead actuator system

Table 2 shows the commercial components selected for the battery powered DC motor system as well as some relevant performance data. This system incorporates lithium-thionyl-chloride (LTC) batteries, which have perhaps the greatest combined power and energy density of any commercially available battery. The batteries drive high-performance 80% efficient DC motors with 85% efficient gearheads to achieve the required joint torques. Note that the gearheads and motors weigh a total of 38.6 kg, leaving 11.4 kg of available battery weight. Note that brushless motors were not used because the added power/weight ratio of the brushless motors were offset by the additional electronics, which would of course be mounted on-board the robot.

Table 2. Selected DC motor system for 90 kg walking robot

Joint	Actuator	Weight (kg)
Hip	Kollmorgen U-9 Servodisc motor w/ Revex 40:1 gearhead. PN: U9M4/GH9-40 Rated power output: 101 W Rated speed: 75 RPM Peak Torque: 51.4 Nm Dimensions: 4.4" Dia. X 5.8"	4.75
Knee	Kollmorgen U-9 Servodisc motor w/ Revex 40:1 gearhead. PN: U9M4/GH9-40	4.75
Ankle	Kollmorgen U-12 Servodisc motor w/ Revex 60:1 gearhead. PN:U12M4/GH12-60 Rated power output: 411 W Rated speed: 50 RPM Peak Torque: 175 Nm Dimensions: 5.9" Dia. X 6.8"	9.8
	Lithium-thionyl-chloride batteries	11.4
	Total weight	50

The key assumptions for the battery-powered DC motor system are summarized as follows:

- Power density of battery: 200 W/kg
- Energy density of battery: 300 kJ/kg
- Efficiency of motor: 80%
- Efficiency of gearhead: 85%
- Efficiency of PWM control: 95%

These assumptions result in the following performance characteristics:

- Maximum power density:

$$\frac{total \; DC \; motor \; power \; output * gearhead \; efficiency}{actuator \; system \; weight} = 27 \text{ W/kg}$$

- Maximum energy density:

$$300 \text{ kJ/kg } (0.85)(0.8)(0.95) = 194 \text{ kJ/kg}$$

- System power density:

$$\frac{total\ DC\ motor\ power\ output * gearhead\ efficiency}{total\ system\ weight} = 11.6 \text{ W/kg}$$

- System energy density:

$$\frac{194\ kJ/kg * 11.4\ kg\ of\ batteries}{total\ system\ weight} = 24.5 \text{ kJ/kg}$$

70% concentration H_2O_2 monopropellant-powered pneumatic actuation system

The 70% H_2O_2 monopropellant-powered system is detailed in Table 3. A 2" diameter pneumatic cylinder running off the pressure reservoir was experimentally determined to deliver a peak power of 400W. This actuator was used for all six joints.

Table 3. Description of monopropellant actuator system weight

Component	Weight (kg)
6 Bimba stainless steel cylinders, 2"Dia x 4" stroke	6.1
1 Parker series 9 fuel valve	0.1
1 steam reservoir	1.0
6 EVC Corp. 4-way proportional valves (SVP-160)	0.9
Spun graphite composite fuel tank w/ Aluminum liner	5.0
70% concentration H_2O_2 fuel	36.9
Total weight	50

The key assumptions for the monopropellant-powered pneumatic actuation system are summarized as follows: The cost of controlling the instantaneous power exerted by the actuator was assumed to add a 100% overhead to the overall energetic cost of the system. Eighty percent efficiency in the cylinder was assumed due to friction losses. The heat of decomposition of 70% H_2O_2 is 1977 kJ/kg [2]. This value represents the total amount of stored chemical energy in the fuel. Further, the efficiency of converting chemical energy to mechanical work was 14.5%. This value was based on calculations using the 1st law of thermodynamics and assuming an ideal gas with constant specific heat undergoing adiabatic expansion [3].

These assumptions result in the following performance characteristics:

- Maximum power density:

$$\frac{total\ actuator\ power\ output}{actuator\ system\ weight} = 183 \text{ W/kg}$$

- Maximum energy density:

$$1977 \text{ kJ/kg } (0.145)(0.5)(0.8) = 115 \text{ kJ/kg}$$

- System power density:

$$\frac{total\ actuator\ power\ output}{total\ system\ weight} = 27 \text{ W/kg}$$

- System energy density:

$$\frac{115\,kJ/kg * 36.9\,kg\ of\ fuel}{total\ system\ weight} = 47.2 \text{ kJ/kg}$$

100% concentration H_2O_2 monopropellant-powered pneumatic actuation system

The efficiency of converting chemical energy to mechanical work for 100% H_2O_2 was calculated as 25%. The rest of the system is assumed to have the same components, efficiencies, and actuator power output as the 70% H_2O_2 system. In reality, this system will be capable of a larger power delivery and would result in a lighter actuation system. However, due to uncertainty in scaling issues, these assumptions will be used as a conservative estimate.

The higher concentration of fuel has more stored chemical energy per unit mass than the 70% H_2O_2 system. Specifically, the heat of decomposition is 2878 kJ/kg, which results in a larger system energy density. The following performance characteristics were calculated for this system:

- Maximum power density: 183 W/kg
- Maximum energy density: 288 kJ/kg
- System power density: 27 W/kg
- System energy density: 118.1 kJ/kg

A summary of the results of the energy density and power density calculations are shown in Figure 4. The square markers correspond to the energy and power densities of the three systems. Note that the 100% H_2O_2 system has approximately 2 times the power density and nearly 5 times the energy density compared to the DC motor-based system. Although this comparison is a rough estimate of performance and should be treated as such, these results suggest that a human scale monopropellant-based system is feasible and well suited for this type of application.
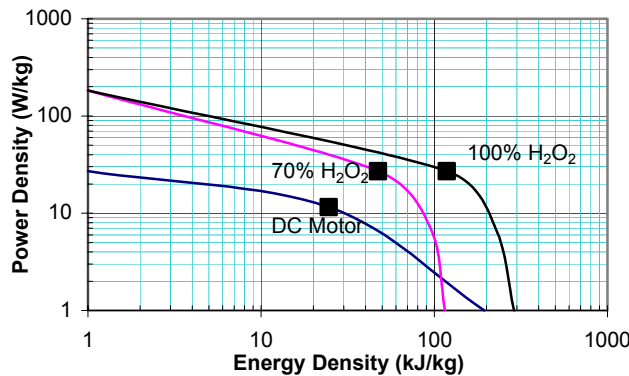

Figure 4. Energy density and power density for various human-scale systems

Experimental Setup and Demonstration

A single degree of freedom arm manipulator was designed and constructed as a demonstration of this technology (Figure 5). A linear pneumatic piston is connected to two links that rotate relative to each other when the piston contracts, similar to a bicep curling motion. Mechanical work is achieved by lifting a weight attached to the extreme end of link 2.
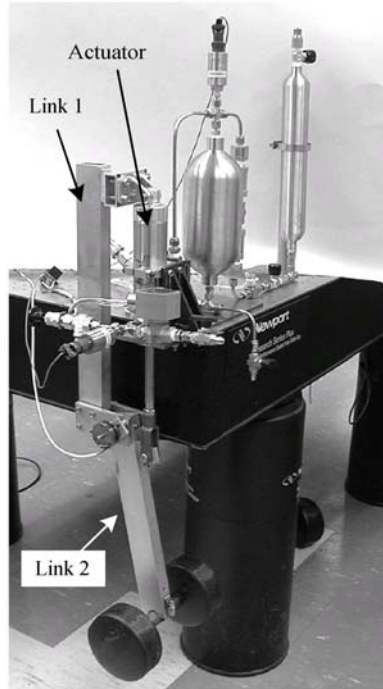
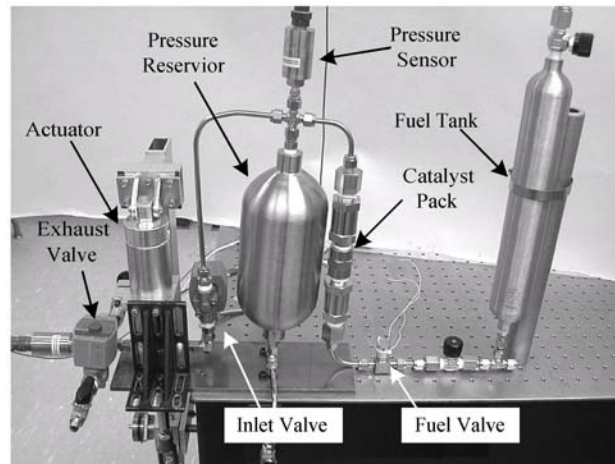**Figure 5. Single degree of freedom arm manipulator**

Figure 6. Monopropellant based actuation system

The monopropellant based actuation system used in the manipulator is detailed in Figure 6. In an analogous manner as shown in Figure 3, 70% hydrogen peroxide is delivered to the catalyst from a pressurized fuel tank through a controlled fuel valve. The gaseous decomposition products are stored in the pressure reservoir and then used to actuate the 2" diameter pneumatic piston. The inlet and exhaust valves are commercial solenoid-operated on/off valves designed for steam. Motion of the end mass is achieved using a simple bang-bang control scheme based on the angular position of link 2. Only upward motion utilizes steam from the pressure reservoir whereas downward motion is provided by gravity as steam is exhausted from the actuator. Figure 7 shows the demonstrator lifting an end mass of 50 lbs.
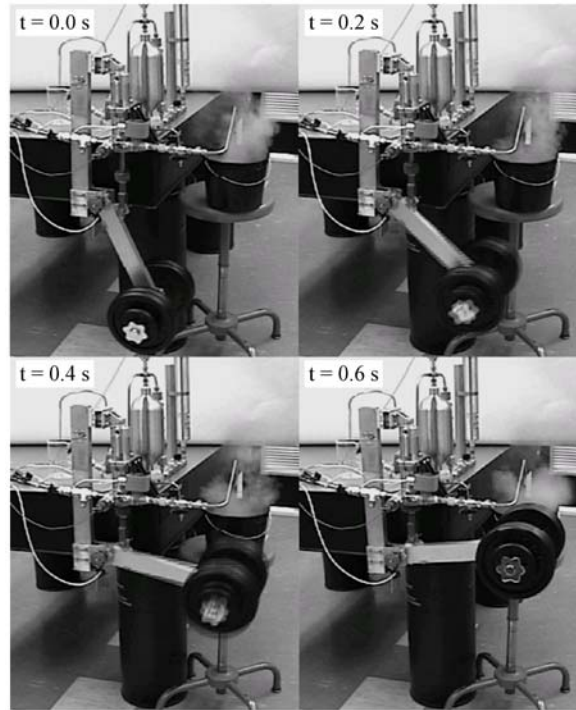
Figure 7. Time series of demonstrator lifting 50lbs

This demonstrator was used to measure the delivered mechanical energy density of the fuel. Figure 8 shows the measured angular position of link 2, fuel pressure, and reservoir pressure as functions of time. The average temperature in the pressure reservoir was measured as 660 °C (350 °F). Fuel consumption was determined from a known initial fuel volume, a known fuel tank volume and by measuring the change in pressure in the fuel tank over the duration of the run. Total mechanical work was calculated as the summation of changes in potential energy for each upward stroke. For this duration, the total mechanical work was measured as 1.4 kJ; the fuel consumption was calculated as 21 g, resulting in a delivered mechanical energy density of 65 kJ/kg for 70% hydrogen peroxide. Therefore, the measured conversion efficiency from chemical potential energy to delivered mechanical work for this system is 3.3%.

Recall, the predicted conversion efficiency was estimated to be 15%. The discrepancy between predicted and measured conversion efficiencies may be attributed to several factors. Heat loss through the walls of the pressure reservoir, the walls of the pneumatic actuator and the lines of the system may contribute appreciable losses to the system. Evidence of this is indicated in the difference between the pressure reservoir temperature (660 °C) and the adiabatic decomposition temperature (840 °C) of 70% hydrogen peroxide. Condensation was observed in both the exhaust steam and in the pressure reservoir at the end of a run, possibly contributing to further losses as the system wastes energy attempting to revaporize the condensate. Friction in the actuator and the manipulator may also be a source of appreciable losses. In addition, flow losses across the inlet valve are also a potential source of loss.
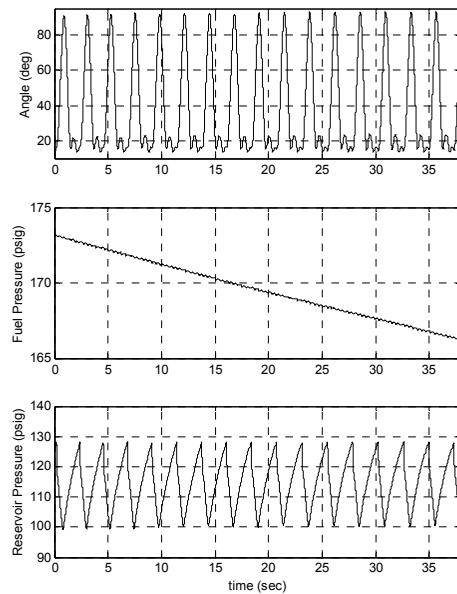
Figure 8. Demonstrator performance data

Using the measured efficiency of 3.3% for the 70% hydrogen peroxide demonstrator, a system utilizing 100% hydrogen peroxide would be capable of delivering 163 kJ/kg. For the six-degree of freedom robotic system of interest, this would result in a system energy density of 66.8 kJ/kg. As compared to a DC motor-based system with a system energy density predicted as 24.5 kJ/kg, such a monopropellant approach shows promise for autonomous robotic actuators. It should be pointed out that this estimate is conservative given that other system configurations, such as direct injection, may exist which would significantly reduce system losses. In addition, there are a number of monopropellant candidates with significantly higher chemical potential energy densities, which could also significantly boost the system performance. In particular, Hydroxyl Ammonium Nitrate (HAN) based monopropellants would be well suited for such a monopropellant-based actuation system.

Conclusions

A monopropellant-based actuation system has been proposed and demonstrated. A liquid monopropellant fuel decomposed using a catalyst offers a simple and direct method of converting chemical potential energy to mechanical work. For the scale of interest, the design tradeoffs between complexity of an energy conversion system and fuel specific energy density make many conventional approaches inappropriate. Preliminary calculations show that a monopropellant-based system possesses attributes more appropriate for the human-scale. To assess this, a system comparison of a monopropellant-based system over a DC motor-based system for a six-degree of freedom autonomous human-scale robot was presented. System energy densities were predicted to be a factor of 2 and 5 times greater for 70% and 100% hydrogen peroxide based actuation systems respectively relative to a DC motor-based system. A single degree of freedom manipulator using a 70% concentration hydrogen peroxide fuel was constructed as a proof of concept device. The measured performance of this demonstrator showed somewhat lower delivered mechanical energy density than predicted. Based on these measurements, the predicted energy density of the six-degree of freedom system using 100% hydrogen peroxide would still be 66.8 kJ/kg compared to 24.5 kJ/kg for the conventional approach. Furthermore, it is expected that design improvements as well as other higher energy monopropellant fuels will significantly enhance performance.

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