Automation, Robotics and Mechatronics –An Introduction to Monopropellant Powered Robotics

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ABSTRACT

This paper describes the design and energetic characterization of an actuator designed to provide enhanced system energy and power density for self-powered robots. The proposed actuator is similar to a typical compressible gas fluid-powered actuator, but pressurizes the respective cylinder chambers via a pair of proportional injector valves, which control the flow of a liquid monopropellant through a pair of catalyst packs and into the respective sides of the double-acting cylinder. This paper describes the design of the proportional injection valves and describes the structure of a force controller for the actuator. Finally, an energetic characterization of the actuator shows improvement relative to prior configurations and marked improvement relative to state of-the-art batteries and motors.

Keywords: - Actuation, robotics, monopropellant power supply, self-powered robot.

I. INTRODUCTION

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 [1].

With regard to this figure of merit, batteries and dc motors capable of providing the requisite power for human scale robot offer reasonable conversion efficiency, but provide relatively low power-source energy density and a similarly low actuator/gear head 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.

1.1 A MONOPROPELLANT POWERED APPROACH

Monopropellants, originally developed in Germany during World War II, have since been utilized in several applications involving power and propulsion, most notably to power gas turbine and rocket engines for underwater and aerospace vehicles. Modern day applications include torpedo propulsion, reaction control thrusters on a multitude of space vehicles, and auxiliary power turbo pumps for aerospace vehicles. This seminar describes the design of a monopropellant-powered actuation system appropriate for human-scale self-powered robots, and presents theoretical and experimental results that indicate the strong potential of this system for high energy density human-scale robot applications. Specifically, with regard to the figure of merit described before .The proposed approach is projected to provide a significantly greater power-source energy density and actuation power density relative to batteries and dc motors, and is projected to provide a higher conversion efficiency and significantly greater actuation system power density relative to a gasoline-powered hydraulic system.[2]

II. LITERATURE REVIEW

Goldfarb et al. describe a system in [1] that utilizes the monopropellant hydrogen peroxide as a power source for the

Position and force control of a pneumatic actuator. The configuration described in [1], called a centralize configuration, converts the energy released as heat via the monopropellant reaction to controlled mechanical work in a manner similar to a standard pneumatic actuation system.

E.J Barth et al. [2] describer Energetic deficiencies in current power supply and actuation technology limit significantly the utility of human scale self-powered robots, such deficiencies have motivated the development of alternative actuators that have the potential to deliver improve energetic characteristics relative to battery-powered servomotors.

B. Khoumeri [3] describes the modelling and control of a direct-injection monopropellant-powered actuator. The actuation system utilizes the catalytic decomposition of a monopropellant, the products of which are directly injected into opposing chambers of a pneumatic cylinder in order to obtain a controllable force source. The system incorporates a pair of proportional liquid fuel valves and a three-way rotary spool valve to control the pressurization and depressurization of each chamber of the actuator.

Noritsugu, T., [4] introduced a model of the catalytic decomposition of the monopropellant and the compressible gas dynamics is derived in order to control the output force of the hot gas actuator function.

McCloy D et al. [5] specifies that monopropellants, originally developed are used for modern day applications include torpedo propulsion, reaction control thrusters on amplitude of space vehicles and auxiliary power turbo pumps for aerospace vehicles..

III. DESCRIPTION OF MONOPROPELLANT ACTUATION SYSTEM

The monopropellant-powered actuation system is similar in several respects to a typical pneumatically actuated system, but rather than utilize a compressor to maintain a high-pressure reservoir, the proposed system utilizes the decomposition of hydrogen peroxide (H_2O_2) to pressurize a reservoir. Peroxide decomposes upon contact with a catalyst. This decomposition is a strongly exothermic reaction that produces water and oxygen in addition to heat. The heat, in turn, vaporizes the water and expands the resulting gaseous mixture of steam and oxygen. Since the liquid peroxide is stored at a high pressure, the resulting gaseous products are similarly at high pressure, and mechanical work can be extracted from the high-pressure gas in a standard pneumatic actuation fashion. [3]

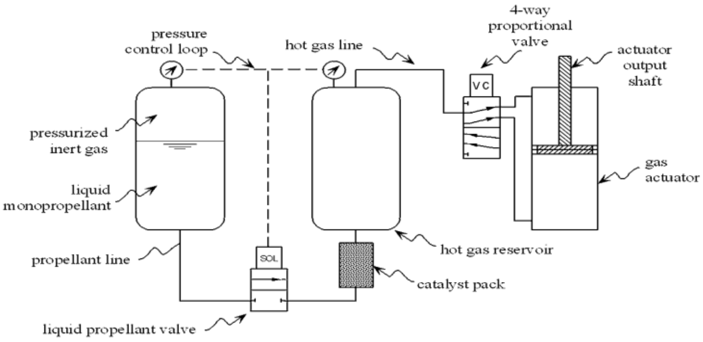
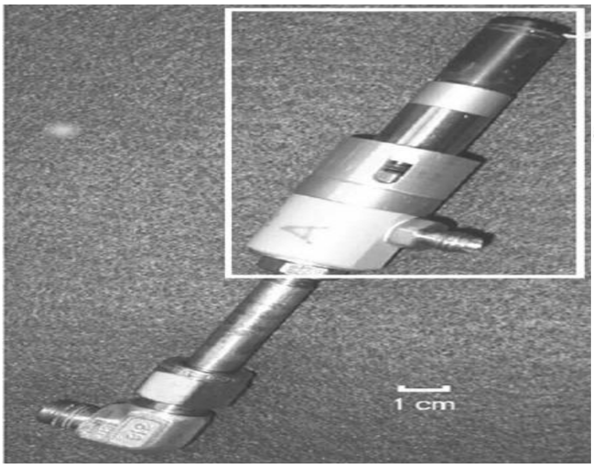


Fig 1: Schematic drawing of the hydrogen peroxide powered actuation system

The conversion of stored chemical energy to controlled mechanical work takes place as follows. The liquid H_2O_2 is stored in a tank pressurized with inert gas (called a blow down 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 four-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.



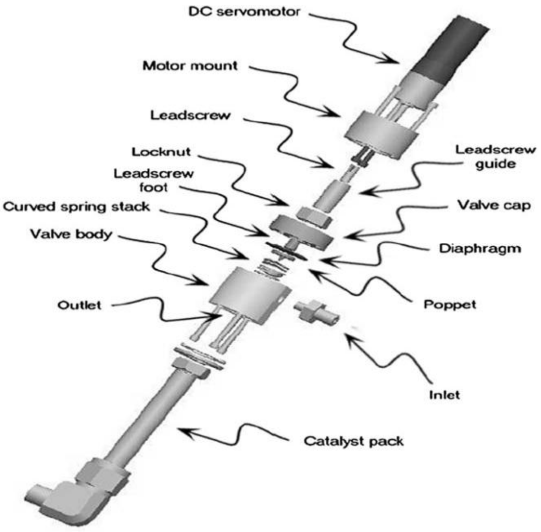


Fig 2: Prototype proportional liquid fuel valve Fig 3: Exploded view of the proportional

valve and catalyst pack

IV. WORKING OF MONOPROPELLANT ACTUATOR PROTOTYPE

4.1 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. 4.

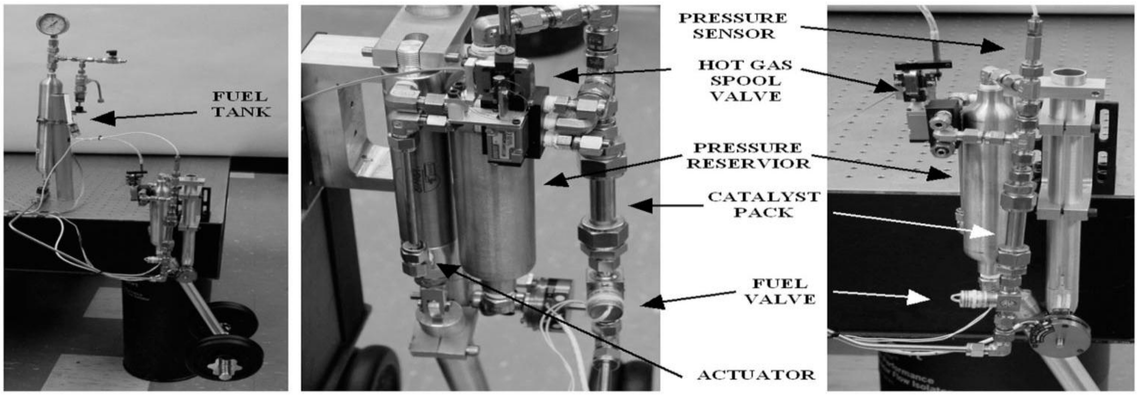


Fig 4: Prototype –single degree of freedom manipulator

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 two-way solenoid-actuated fuel valve through a catalyst pack and into a stainless-steel reservoir. The catalyst pack consists of a 5-cm-long (2 in), 1.25-cm-diameter (0.5 in) stainless-steel tube packed with catalyst material. A pressure sensor 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 by a four-way spool valve, modified for proportional operation by replacing the solenoid actuator with a thermally isolated voice coil. The valve spool displacement is measured with a differential variable reluctance transducer (DVRT) 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.

4.2 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 a high-bandwidth (i.e., approximately10 Hz) position control of the valve spool. 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 position, velocity, acceleration (PVA) feedback controller, which commands the valve spool position.[2]

V. EXPERIMENTATION

5.1. LOAD PROFILE

Since the actuator relies on gas as an energetic medium, and since the actuation system is not designed to utilize energy resulting from condensation of the steam (steam quality less than 100%), the energy required to vaporize the water will not be recovered and as a result the conversion efficiency is lower than if actuation system included partial condensation.. Partial condensation occurs as a result of this load profile, leaving 70% quality steam in the actuator. This load profile would yield a theoretical efficiency of 39 %(calculated theoretically) for the 70% peroxide solution.

5.2 UNINSULATED EXPERIMENTS

Experiments were conducted to measure the previously calculated conversion efficiency. A 70% peroxide solution was used as the propellant to maintain acceptable temperatures for commercially available components. For these experiments, the single-degree-of-freedom manipulator was commanded to move the 11 kg mass through a 30-degree amplitude, 1-Hz sinusoidal motion. The work output was computed indirectly by measuring the angle and, in post-processing, computing the actuation torque using a model of the load. The instantaneous power and average power could then be calculated. The propellant mass consumption was measured indirectly by recording the pressure of the nitrogen gas in the blow down 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 is easily computed from the known volume and density. The conversion efficiency is then computed over an integer number of cycles with the heat of decomposition of 70% hydrogen peroxide solution.

5.3 INSULATED EXPERIMENTS

In order to improve the measured conversion efficiency, the catalyst pack, reservoir, and actuator were wrapped in insulating tape, as shown in Fig. 6, and measurement of the conversion efficiency was repeated. For the insulated case, the experimentally determined conversion efficiency was found to be 9 %.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 12 %, the difference presumably due to control inefficiency (i.e., intermittent exhausts).

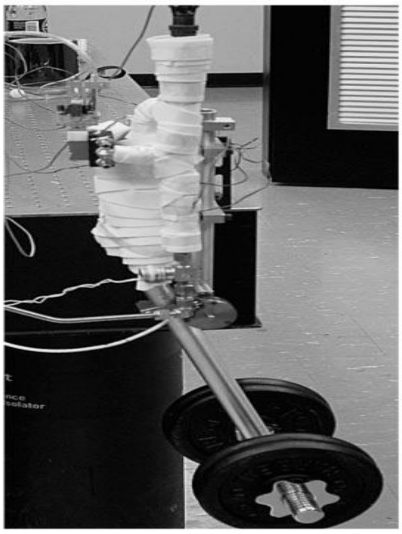


Fig. 6: Monopropellant actuator prototype wrapped with insulating tape and instrumented with thermocouples for measurement of surface temperature.

For purposes of comparison, the best commercially available rechargeable batteries have energy densities of approximately180 KJ/Kg (e.g., Evercel M40-12 nickel zinc, or SAFT 27 10 LAS silver zinc). A rare-earth permanent-magnet dc motor with a harmonic drive gear head with output characteristics capable of achieving the trajectory specified by Table I, has a power density of approximately 48 W/Kg. 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 pulse width-modulation (PWM) control, the motor, and the gear head. 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 gear head efficiency was estimated based on manufacturer data to be 65%. The resulting actuation potential for this type of system would therefore be 4.8 KJ KW/Kg. 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.

VI.CONCLUSION

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.

Steam powered robots are a possibility in the future provided the limitations of the existing prototype is done away with. A better actuation potential can be obtained by providing better insulation to the prototype thereby reducing the heat loss. Another challenge before researchers is to manufacture parts that can withstand the high temperatures generated on decomposition of 100% H_2O_2 .With the introduction of better controls, fuel and insulation, the se robots could function effectively and economically.

The proposed power supply was found to be a feasible solution to the problem of providing a long lasting power supply to robots that can actually work. Moreover the power output could be easily adjusted by controlling the rate of flow of the monopropellant. Although a full size human scale robot powered by a monopropellant is yet to be made, the experimental results obtained from a single degree of freedom manipulator proves the feasibility of such a system.

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