Investigation of Mechanical Energy Storage System For Agile Mobile Robot Motion

Counter Rotating Flywheel Controlled Hovering Robot

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***Abstract*—** In this paper, we present our research efforts which investigates efficiency of mechanical energy transfer from flywheel to the overall mobile hovering robot body not only with simulations but also with real world experiments. To generate varying amounts of inertia with respect to rotation requirements, a counter rotating flywheel system is developed and multiple angular motion profiles are applied within simulations and experiments. Mechanical design, simulation details, manufacturing steps and various test cases to generate different amount of torque are presented at the end of the paper. It is shown that, with accurate parameters, mechanical energy storage system is capable of generating required amount of forces to increase the maneuverability of a hovering mobile robot while it reduces its internal mechanical disturbances compared to a traditional control schema for a path following mission.

Keywords*—mechanical energy storage, fly wheel, reaction wheel, torque control*

I. INTRODUCTION

Mobile robots are getting parts of our life increasingly. Autonomous ground vehicles are one of the most studied systems. They are capable of dealing with heavy payload and could be used for various purposes from remote planet observation to transportation systems. With enhanced battery capacity, they can reach to a high speed. However, when systems faces with an obstacle –such as a river— it won't be able to cross the obstacle. A quadcopter is an ideal system that can deal with such obstacle, however it has pretty limited durability due to high power consumption.

Next generation humanoids are expected to coexist within the human environment. A complex gait motion and maintaining balance under sudden environmental changes are required to control the system. However, these models have their limitations: they represent entire structure of linkages –robot body—only as a point mass and do not characterize the significant centroidal moment of inertia of the body. The body's state of balance is closely related to its rotational equilibrium which is dependent on its angular momentum rate change. Additional torque could be useful to support this control structure. Mechanisms with momentum wheels such as NASA Small Explorer Program's SWAS device [1] and "Cubli" [2] were studied to enhance the angular control and robustness of structures. The SWAS' balancing mechanism is a wheel which is unique in its small size and can generate highly

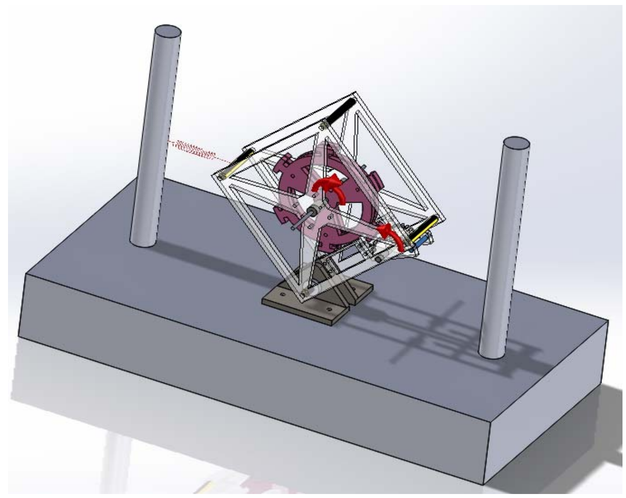

Fig. 1. Solid model used for motion simulation

controllable torque. Reaction/momentum wheels are mechanisms used to provide attitude control and stability on spacecraft. By adding or removing energy from the flywheel, torque is applied to a single axis of the spacecraft, causing it to react by rotating. By maintaining flywheel rotation, called momentum, a single axis of the spacecraft is stabilized. Several reaction/momentum wheels can be used to provide full three-axis attitude control and stability.

Another research effort –the Cubli— is a 15 cm. sided cube than can jump up, balance on its corner and walk across a platform. It uses off-the-shelf motors, batteries and electronic components. This cube requires a sudden release of energy for it to jump and balance on one corner. Momentum wheels are used to store energy and also implement a reaction torque based control. The cube is compact and self-contained.

On the other hand, a control moment gyroscope (CMG) can be also used for the altitude and heading control. For a smaller structure such as earth observing satellites, reaction wheels are feasible and torque generated by the reaction wheels is competent to drive the system in the required direction or to control its altitude [3]. The reaction wheels are specifically volumetric efficient and can store a high amount of momentum depending upon the mass, volume of the wheel and its rotational speed. For advanced engineering operation systems like a CubeSat, the mass and volume of the reaction wheel play a vital role since there are a lot of design constrains. The use of Euler's momentum equation makes it possible to determine mass and volume requirements for a reaction wheel and to quantify the ample amount of torque depending on the purpose of the mission [4].

While all above systems have their pros and cons, we developed a hybrid system to study various dynamical systems: a hovering robot [5]. The advantage of a hovering body is that it can traverse through nearly any non-porous surface. However, system requires a wide turn radius if it is controlled with differential drive forward thrusters which limits system's mobility.

To address this challenge, we assembled a mechanical energy storage system –a counter rotating flywheel— to investigate possible use of flywheel on top of the robot. System is shown in Fig. 1 represents the flywheels and a spring to measure the response behavior. Once the flywheel rotates at a high speed, it stores energy. If the robot is expected to follow a planned path and when a hard turn –such as 45˚ to 90˚ is required—a braking mechanism stops the wheel instantaneously to transfer the inertia to the whole body. Details of the hovering robot is explained in a previous paper [5].

In this paper, we present our research efforts which investigates efficiency of energy transfer from flywheel to the overall mobile robot body not only with simulations but also with real world experiments. A spring is attached to the frame of the flywheel and its displacement is measured to determine the forces that can be generated. To generate varying amount of inertia with respect to rotation requirements of path following algorithm, a counter rotating flywheel system is developed. Varying angular velocity profiles for individual wheels are applied. Mechanical design, simulation setup, manufacturing steps and various test cases to generate different amount of torque are presented at the end of the paper.

Next section explains spring parameter identification experiment which is used in both simulations and experimental calculations. It is followed by simulation and experimental setup sections. Finally, results are listed and paper is concluded with remarks and future work.

II. Parameter Identification

A standard experimental procedure [6] was performed on an extension spring to verify the spring constant. The experimental procedure was to fix one end of the spring and hang a known weight of 214 grams on the other end to check for deflection using a millimeter scale. The experiment gave out reasonable values of an average deflection of 17mm for each time the spring was tested. An average of the measured values was considered for accuracy. Hooke's law used is given by

$$F = -k * x \tag{1}$$

where "F" is the force exerted by spring and is always in the opposite direction. "k" is the spring constant and "x" is the amount of deflection. Upon further calculations, the spring constant was calculated to be 12.588 g/cm. Experimental procedure is presented in Fig. 2.

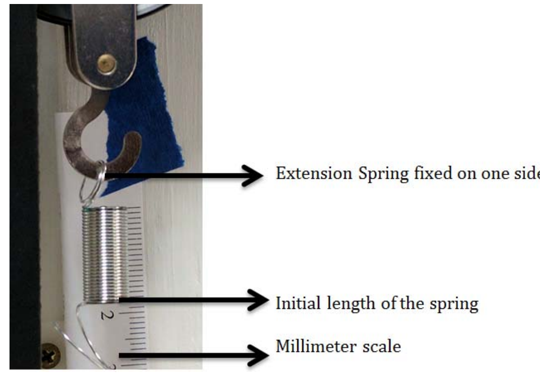

Fig. 2. Spring constant calculation experiment with a known mass

III. Modeling and Simulation of Momentum Wheel Mechanism

The model shown in Fig. 3 is a 3D solid model as well as a working model representation of the physical system. The parts in the assembly model are constrained to provide the motion that the real assembly experiences. Along with motion constraints, motor torques, to provide rotational motion, and linear spring are applied to the model for the purpose of conducting kinematic motion study analysis. Thus A) the components of the assembly, B) assembly motion constraints and C) Kinematic motion simulation study parameters and setup are herein discussed in this section.

A. Components of the momentum wheel mechanism assembly

Square plates: Square plates are made up of acrylic sheets that laser cut into square shapes. Acrylic sheets are light in weight and compact.

Momentum wheels: Also known as flywheels. Flywheels are used to store and supply continuous energy through moment of inertia. These momentum wheels are mounted onto the square plates

DC Motor: DC motor is a rotary electrical system used to convert electrical energy into mechanical energy. DC motors are used to rotate the flywheel at high speeds. Two DC motors as used to obtain counter rotating flywheel dynamics.

Servo motor kit: Servo motor kit consists of a servo motor and links. The servo motor is used for braking the flywheel that is rotating in high speeds to create an inertial effect on the square plates.

Shaft coupling: It is used to couple the flywheel and the motor shaft for rotation of the flywheel.

Connecting Shaft: It is fixed to the flywheel and coupled to the DC motor using shaft coupling.

Motor Mount: It is used to mount the motor on the square plate in the required position.

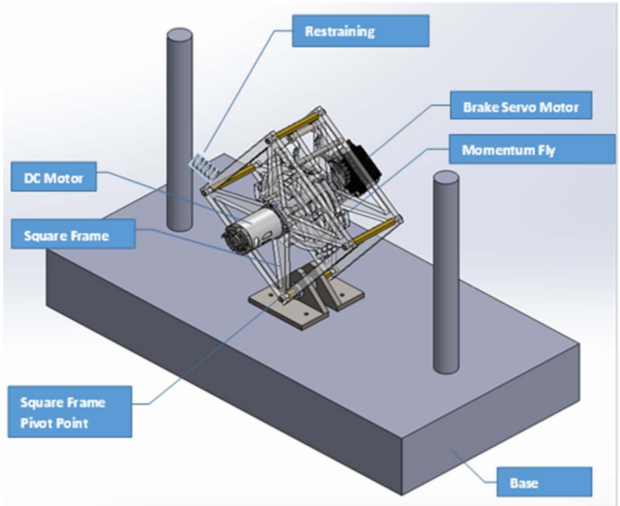

Fig. 3. Simulation components

B. Assembly Constraints

The square frame housing, DC and brake servo motors are assembled such that they are considered as rigid, that there is no relative motion between each other. The flywheels and the brake mechanism are assembled to the square frame, however both move / rotate relative to the square frame. The flywheels rotate about the center of the square frame whereas the rotation of the brake occurs offset from the center of the square frame. The entire square frame chassis rotates about a pivot point which is fixed relative to the base. Linear spring is applied between one of the vertical support shafts and one side of the square frame to constrain the angular rotation of the square frame.

C. Kinematics Motion Study Simulation parameters and setup

Parameters used for the simulation are as following:

Linear Spring model: k = 0.704895 lbf/in and free length = 3.38278149in
Braking Mechanism RPM: CCW 2rpm constant motor applied to brake mechanism
Front flywheel: 20 rpm constant motor applied. CW rotation
Rear flywheel: Motor applied with varied rpm from 20rpm to 0rpm (constant). CCW rotation.
Contacts: Solid body contact applied between brake mechanism and both of the flywheels so that the brake mechanism shaft will stop when the shaft engages the flywheel teeth. Solid body contact applied between the square frame and base
Simulation time: About 20 seconds

D. Simulation Results

First simulation is executed to analyze the behavior of internal disturbances in the system. With same angular velocity, both wheels are rotated in counter direction and brake is applied at around 9th second. Torque plot is shown in Fig. 4.

System torque behavior is oscillatory (harmonic like motion) since there is a spring connected to the body of the flywheels. Spring displacement is also used as a benchmark for the real world experiment. First 9 seconds of Fig. 4 represents internal vibration caused behavior. At about ~9th second, claw hits the wheel and brakes one of them before the other one. This is the amount of torque that can be generated while both of them rotate with the same RPM.

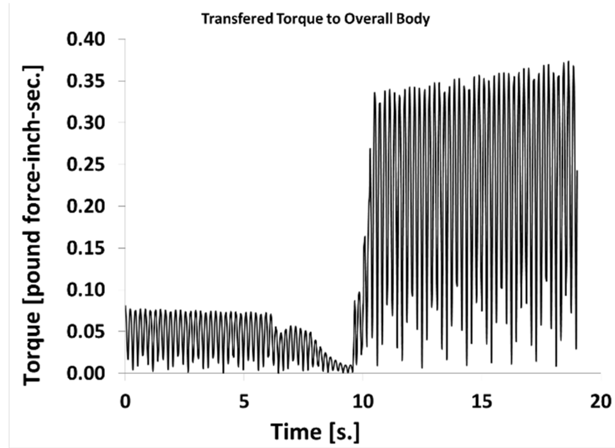

Fig. 4. Torque plot, internal disturbances and reaction after brake is applied

Second simulation applies 10% angular velocity difference between wheels. It is observed that due to non-equal rotational velocities, constant internal disturbance is higher prior to system is braked. After brake is applied at about 7th second, there is a highly dynamic transient response occurred till claw catches both of the wheels. Finally, peak torque is about .45 pound force inch second that is 25% higher than the previous experiment once constant initial disturbances are subtracted from peak points. Plot is shown in Fig. 5.

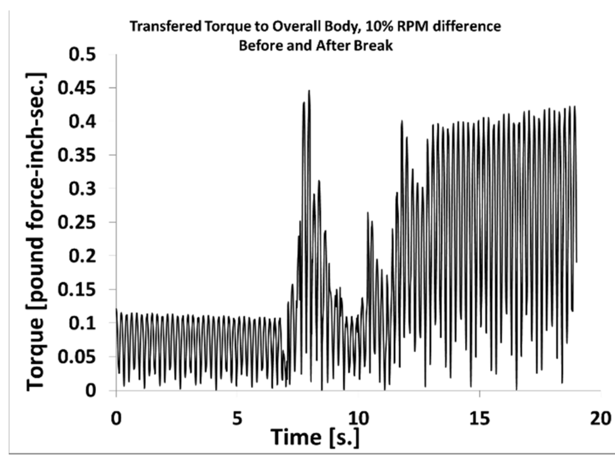

Fig. 5. Torque plot, 10% difference in angular velocities before brake is applied

IV. Experimental Setup

Momentum wheels are mounted on the faces of the square plates(2D laser cut acrylic sheets) with a pre-calculated mass and dimensions. These momentum wheels rotate with high angular velocities and when braked suddenly, they transfer the momentum to the overall structure. The momentum wheels are driven by high speed DC motors to achieve high angular velocities.

A. System Components

Two square plates that were made up of acrylic sheets were laser cut for high accuracy. Acrylic sheets were used as they are light in weight, compact and low cost.

Two flywheels were used to store and supply continuously available energy through moment of inertia. These momentum wheels were mounted on to the square plates. Acrylic sheets were used for the flywheels as well. Two DC motors were used to rotate the flywheel at high speeds. These motors helped obtain counter rotation of the flywheels. The servo motor was used for braking the flywheel that is rotating in high speeds to create an inertial effect on the square plates. Shaft couplings were used to couple the flywheel and the motor shaft for rotation of the flywheel. A connecting shaft was fixed to the flywheel and coupled to the DC motor using a shaft coupling. Motor mounts were used to mount the motor on the square plate in the required position. Components and quantities are listed in Table 1.

B. Plates, Flywheels and brakes

Two plates, flywheels and brakes of known dimensions were designed in a CAD software and were cut on an acrylic sheet using a 2D laser cutting machine. Brake mechanism is shown in Fig. 6.

TABLE I. SYSTEM COMPONENTS

#	Bill of Materials	
	Component	***Quantity***
1	Square plate	2
2	Momentum wheels	2
3	DC Motor	2
4	Gyroscope (IMU)	2
5	Servo Motor Kit	2
6	Rotary magnetic encoder kit	1
7	Motor Controller	3
8	Hall effect sensor	4
9	Shaft Coupling	2
1	Connecting Shaft	2
11	Motor mount	2

C. Assembly

Two DC motors were mounted onto the plates using a motor mount. Couplings were used to connect the motor shaft to the flywheels.

D. Pillar screws were used to attach both the plates.

A servo motor was mounted on one of the plate. To which the brake was attached.

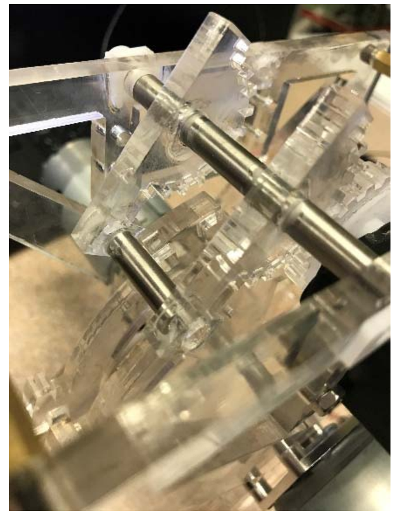

Fig. 6. Braking mechamism

E. Control Board

Arduino Uno and Arduino motor shield Rev 3 were used for the three motors. They were programmed in such a way that the flywheels rotate in opposite directions and to operate the brake mechanism. The setup was connected to an external power source. The entire setup was mounted on a predesigned hovercraft. Figure 7 represents the boards used.

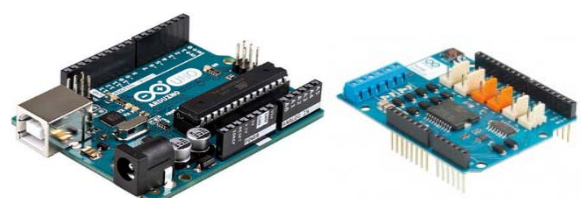

Fig. 7. Single board Controller and power distrubition expansion board

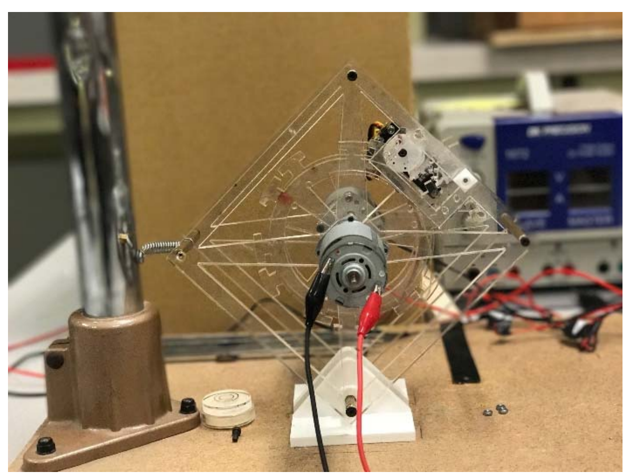

Fig. 8. Final product: a spring is attached to the flywheel body to plot the response behaviour

F. Use of Flywheel

A flywheel is a rotating mechanical device that is used to store rotational energy. They use the principle of moment of inertia. The amount of energy stored in a flywheel is proportional to the square of its rotational speed. Energy is transferred into the flywheel by the application of torque to it, thereby increasing its rotational speed and hence its stored energy.

Uses of flywheel are to provide continuous energy when the energy source is discontinuous, to deliver energy at rates beyond ability of a continuous energy source and to control the orientation of a mechanical system. Final system design is shown in Fig. 8.

V. EXPERIMENTAL RESULTS

The experimental setup was powered using a switching power supply. A current of 3A was applied to each of the motor such that both the motors rotate the flywheel in the same direction. The current was gradually increased to 3A for each of the motor one at a time. Initially the motor M1 was actuated by applying low current and gradually increased to 3A smoothly, since the motors were not self-starting at low currents due to the attached mass on the motor shaft which includes the coupling, flywheel connection shaft and the flywheel.

Displacement of the spring is measured with a 240 fps camera and displacement is logged manually. Resulting plot representing spring displacement is shown in Fig. 9.

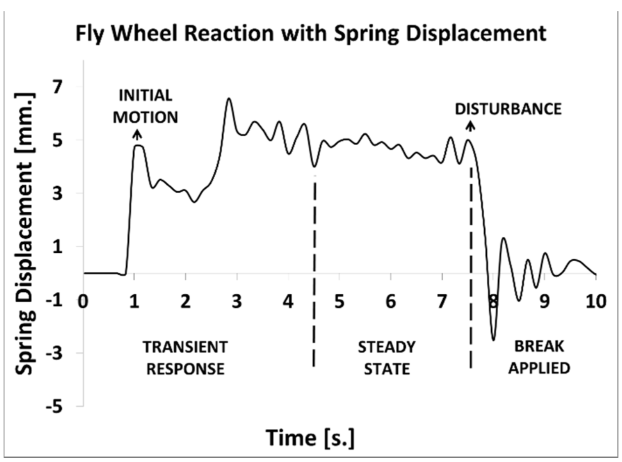

Fig. 9. Spring displacement behaviour during the experiment

As the current was applied and gradually increased from time 0 to ~0.8 seconds there was no movement in the motor and after ~0.8 seconds the motors picked up the rotary motion and the revolution per minute of the flywheel increased generating a moment of inertia. Torque on the system displaces the spring to a significant length and due to the restoring forces of the spring and the torque, a harmonic motion was observed in the system. The delay in the second motor was allowed due to current output limitations of the power source which is for a very short span of time.

The second peak observed during the transient response of the system was due to the start-up of the second motor and the transient response continued while both motors rotating in the same direction with approximately same amount of current applied. As the system settles down, fluctuations began to decay and response reaches to a steady state from ~4.5 seconds to ~7.7 seconds where both the motors are supplied ~3A current each. During the steady state phase, a continuous noise caused the fluctuations. Fundamental reason of the noise is vibration in the system, which occurred due to the eccentricity in the rotation of the flywheels and minor assembly errors. At about ~7.7 seconds, the power was cut off to observe the reaction of the system as it displaced the spring due to moment of inertia developed during the rotation of the flywheels. As soon as the power was cut off, a harmonic motion was observed in the system displacing the spring harmonically. This harmonic motion eventually faded away due to friction and the system reached to idle state at about ~10.1 seconds.

VI. CONCLUSION AND FUTURE WORK

The purpose of a 2D momentum wheel used in the research is to generate a predefined resultant torque to steer the hovercraft in the required direction which is determined by a path generation algorithm. While system requires a wide turn radius without fly wheels, it is shown that a counter rotating mechanism is feasible to use to control the heading of the mobile robot.

Since system utilizes counter rotating wheels, internal disturbance is minimized especially in the beginning of the angular motion. Additionally, it is observed that varying magnitude of torques could be generated by setting different angular velocities of the wheels.

The amount of net torque generated has a non-linear behavior with respect to varying angular velocity ratios. It requires an additional study to generate the transfer function which governs the system behavior.

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