The Design and Control of a Low-Power, Upper-Limb Prosthesis

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***Abstract* — Control moment gyroscopes (CMGs) offer a unique approach to address power consumption issues that currently limit the design of prosthetic limbs. CMGs generate large output torques while requiring less power than conventional actuators. This advance is possible because CMGs conserve angular momentum without increasing the kinetic energy of the system, providing high-agility, low-power movements. We have designed a novel, three degree-of-freedom prosthetic arm actuated with small-scale CMGs. Each of the three segments contains one CMG scissored pair, which allows precise control over joint torques and accelerations. The prototype arm will have a workspace of 360 degrees of rotation about each joint axis, although it will be limited to physiological standards. The motions replicate elbow flexion/extension, wrist flexion/extension, and forearm supination/pronation. We will implement real-time, myoelectric control using electromyographic (EMG) signals recorded from the biceps brachii for the elbow joint, brachioradialis for the forearm, and the flexor carpi radialis and extensor digitorum communis for the wrist. The control system will correlate the EMG signals with output force of the arm and produce corresponding movements that mimic those produced by humans during voluntary contractions. Ultimately, our arm will serve as a prototype for future designs that utilize the unique characteristics of CMGs to enable upper-limb amputees to return to normal function.**

I. INTRODUCTION

Rehabilitation engineering is a growing field that encompasses topics such as mobility-assist devices, custom orthotics and braces, powered exoskeletons, and prosthetic limbs. As a result of an increasing number of health concerns that necessitate amputation, many researchers have advanced the design and function of devices such as upper-limb prostheses.

This study aims to design and control a three degree-of-freedom prosthetic arm with reduced power consumption and high torque output. This is achieved using control moment gyroscope (CMGs) actuation. In a CMG, a gimbal tilts a spinning rotor causing a gyroscopic torque perpendicular to the rotor spin axis and the gimbal axis. Scissored pairs of CMGs rotate with equal and opposite gimbal angles, which produces a net torque along the arm segment's axis of rotation. Scissored pairs of CMGs rotate with equal and opposite gimbal angles which produces a net angular momentum vector along a line or axis of rotation [2]. The arm accelerates when the CMGs are gimbaled at a constant velocity and retains a constant velocity when the CMGs are not moving and tilted away from their initial gimbal angles.

According to the Law of Conservation of Angular Momentum, torque applied to the CMG by the body is also applied to the body by the CMG. This allows the scissored pair to require substantially less power to generate large output torques than conventional actuators [2]. Therefore, this design will retain output torque for longer periods of time without requiring its power supply to be re-charged.

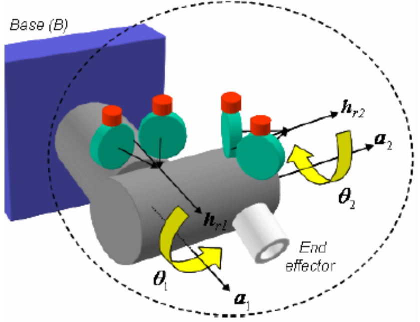

Fig. 1. A model illustrating the angular momentum exchange due to the CMG scissored pair [2].

Electromyographic (EMG) signals will serve as the control inputs in order to replicate the movements of able-bodied subjects. An EMG signal is defined as the electrical expression of the neuromuscular activation associated with a contracting muscle. Ideally, the CMG-actuated arm will serve as a foundation for longer-lasting, improved upper-limb prosthesis in the future.

II. METHODS

A. CMG Actuators

Each joint in our arm contains a scissored pair of CMGs that allow for joint rotation. The magnitude of output torque of the arm is governed by both the mass moment of inertia of the spinning rotor and the speed at which the rotor is spinning.

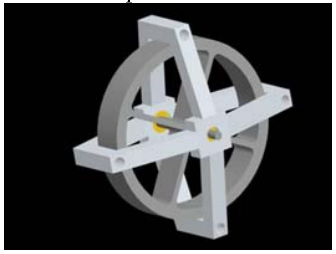

Fig. 2. The basic CMG design including the rotor and gimbal casing.

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B. *Physical Arm Design*

The prototype physical arm structure will be constructed of extruded acrylic tubes with aluminum inserts. The arm will be slightly larger than current prosthetic limbs because of the CMGs' dependence on large rotor inertias to generate substantial joint torques. The elbow and forearm are 6 inches in diameter and the wrist is 4.5 inches in diameter.

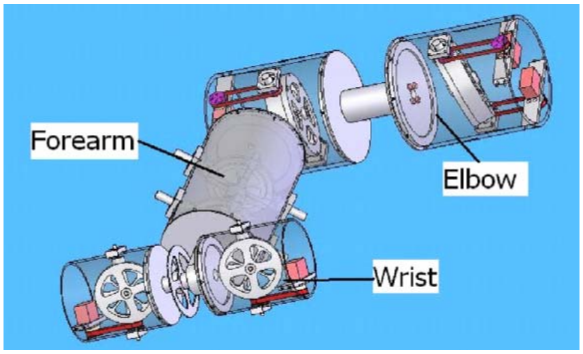

Fig. 3. CAD model of the arm's physical structure. Note that each segment contains a scissored pair of CMGs about its axis of rotation.

The arm will use EMG signals recorded from isometric, bicep contractions, during which the muscle is activated without being able to lengthen or shorten, thus eliminating noise caused by motion artifacts. Two detection surfaces are used during the recording, a ground and one located on the muscle of interest. In this configuration, the shape and area of the detection surfaces and the distance between the detection surfaces are important factors because they affect the amplitude and the frequency content of the signal. The raw EMG data was notch filtered at 60 Hz during the collection process to eliminate direct environment noise. The EMG signals acquired from the able-bodied subject are then high-pass filtered at 20 Hz, rectified, and then low-pass filtered at 2 Hz [1] in order to generate a smooth curve that corresponds to the input voltage for the control algorithm.

III. RESULTS AND DISCUSSION

A. *CMG Output Torques & Load Capabilities*

The three scissored pairs of CMGs are capable of outputting maximum torques when gimbaled to 45 degrees. The elbow CMGs require the most output torque because they have the largest torsional moment arm, 18 inches. The forearm and wrist CMGs rotate about axes with smaller moment arms, 4 in. and 4 in. respectively. The estimated values of output torque at each joint are listed in Table 1. The values assume that the CMGs are spun up to 13,000RPM.

The maximum, estimated load that the arm can move with all three segments is approximately 6 lbs.

Table 1 – Joint torques generated by CMGs.

Joint	**Output Torques (lbf-ft)**	**Peak Power Input (Watts)**
Elbow	14.10	41.25
Forearm	1.85	34.05
Wrist	4.84	34.05

B. *EMG Filtering*

The recorded EMG signals are correlated to output force of the arm that generate corresponding movements. A desktop computer and real-time control board, dSPACE®, allows the signal to be high-pass filtered with a second-order Butterworth filter (cut-off frequency 20 Hz) to remove movement artifact, full-wave rectified, and low-pass filtered with a second order Butterworth filter (cut-off frequency 2 Hz) to smooth the signal [1]. A filtered biceps signal used to control the elbow joint in the control system is illustrated in Fig. 4.

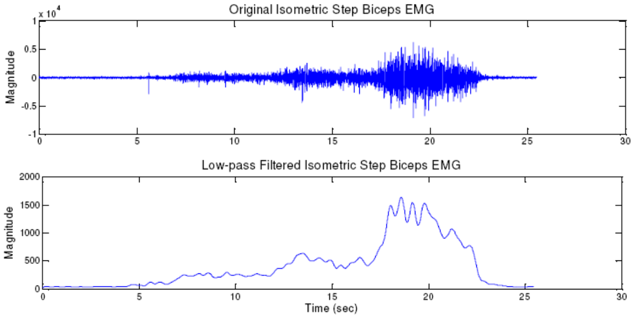

Fig. 4. Filtered EMG data from the biceps that will be used as control inputs for the elbow joint.

IV. CONCLUSION

CMGs offer a novel approach to actuating prosthetic limbs that improves the power efficiency of the robotic arm without sacrificing its agility. We have developed a three degree-of-freedom prototype arm that will demonstrate the unique advantages of the CMGs. Additionally, real-time, myoelectric control will be used to validate the use of the arm as a prosthesis. In future work, improved neural control methods and more efficient CMG designs will be used to include task oriented movements.

ACKNOWLEDGEMENTS

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