INTRODUCTION
In a spacecraft’s flight and attitude control, it requires an external force, or torque, which is often provided by a minimum of three reaction wheels. As an alternative, we propose to use of a magnetically levitated reaction sphere (MSRS) for satellite’s attitude control. In our design, the sphere can be angularly accelerated about any axis by a three dimensional (3D) motor, making the attitude of the spacecraft in all axes controllable by a single device. A sphere can always give maximum inertia, independent of its rotational axis. Thus using reaction sphere can reach smaller size and mass, which is an essential consideration for space device design.

This paper takes initial steps to study the performance of high speed magnetically suspended reaction sphere on small satellites by demonstrating a single dimensional reaction sphere. This 1D demonstration presents a motor with a solid spherical rotor magnetically levitated in three translation directions, and which can be driven and thus control momentum about the vertical axis. For the suspension of the sphere, single dimensional magnetic levitation in vertical direction and bearingless motor around the rotor are combined. For the driving method, the hysteresis motor principle is selected due to its good property of synchronous running, smooth, vibration-free operation, constant torque and moderate current draw during start up.

This paper focuses on the design characteristics of the suspension and driving system of the 1D MSRS. What follows are the simulation and experimental results that demonstrate the performance of the 1D MSRS.

HARDWARE DESIGN AND INTEGRATION
The 1D MSRS is a motor with a magnetically levitated spherical rotor that can rotate and stores momentum about the vertical axis.

MODELING, CONTROL AND EXPERIMENTS
In this section modeling and control of the 1D MSRS’s suspension and rotation is presented.
Bearingless motor
In order to drive the sphere’s spinning and suspension simultaneously, a bearingless motor is adopted in the 1D MSRS. Bearingless motor is achieved by using two sets of 3 phase winding on a single stator. By correctly configure and control current in these motor windings, the machine can generate radial force for suspension as well as torque for spinning with only one stator. The frequency response of the lateral position control loop is measured under different excitation current amplitude in the driving winding (here the 4 pole motor winding). The measured Bode plots is depicted in Figure 3.

Hysteresis Motor
In this paper a equivalent circuit model of hysteresis motor is being used to analyze the dynamic behavior of the one-axis motor reaction sphere.

EXPERIMENTAL AND SIMULATION RESULTS
Figure 4 presents the acceleration curves of the 1D MSRS under different amplitudes of excitation current. Data shows that with 0.7 A excitation current, the sphere can reach the synchronous speed of 30 Hz (1800 rpm) within 6 seconds. Also, a starting torque of \(8.15 \times 10^{-3} \text{N.m}\) is demonstrated under 0.7 A exciting current.

Figure 5 shows the starting angular speed of the 1-D MSRS from simulation and measurement. Good agreement between simulation and experimental data confirms the validity of the equivalent circuit model for analysis of the 1D MSRS.

CONCLUSION AND FUTURE WORK
The development of a magnetically suspended reaction sphere based on a single degree-of-freedom hysteresis drive is presented in this paper. Magnetic suspension, bearingless drive and hysteresis motor principles are used in the design for 1D MSRS. An equivalent circuit model for hysteresis motor is used to analyze the dynamic behavior of the 1D MSRS. Further research on vibration suppression, power efficiency optimization and motor performance tests in closed-loop speed control for the 1D MSRS is ongoing in the Precision Motion Control Lab at MIT.

With these results in hand, the next steps to take in the future would be the design of a three-dimensional reaction sphere. The performance of the 1D MSRS demonstrates that bearingless motor is a promising method to solve the field coupling between motor and bearing function for a 3D magnetic levitated motor, and that the hysteresis motor is a possible motor concept for the development of a all degree-of-freedom reaction sphere.