UPGRADE OF THE GODDARD SPACE FLIGHT CENTER'S MASS PROPERTIES MEASURING FACILITY

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ABSTRACT

Goddard Space Flight Center has a Mass Properties Measuring Facility (MPMF), which is used to measure weight, center of gravity, moment of inertia, and product of inertia of satellites and space flight hardware. The system was originally purchased more than 30 years ago. While the MPMF was still in good mechanical condition, the measurement and control subsystem had begun to experience more frequent component failures. Many of the outdated, discrete components in the system are no longer available for replacement. A decision was made to upgrade the measurement and control subsystem of the MPMF to improve its reliability and reduce the chance of component failures leading to extended facility outages. This paper will describe details of the upgraded subsystems and summarize the new performance capabilities of the system.

INTRODUCTION

The Mass Properties Measuring Facility (MPMF) at the Goddard Space Flight Center (GSFC), which measures weight, center of gravity (CG), moment of inertia (MOI), and product of inertia (POI), was originally purchased in the early 1970's from Miller Research Corporation (MRC). In recent years, there has been a growing concern regarding the maintenance and reliability of the system and it's impact on project test schedules. Mechanically, the system is still in very good condition. However, the measurement and control console has been experiencing more frequent failures and many console components use antiquated relay technology and some are no longer available from the vendor. Options for updating the system's technology, improving its reliability, and mitigating payload risk were developed. The first option was to contract the work out. The proposal that was received called for replacing the hemispherical air bearing and drive motor with an integral bearing and motor assembly, as well as replacing the measurement and control systems. The total cost was estimated at $178,000. Under this proposal, the facility would also be unavailable for an extended period. The other option was to upgrade the measurement and control system in-house at an estimated cost of $81,000 while only losing use of the facility for 1-2 weeks. Based on the cost and the expected availability of the MPMF for testing during the upgrade process, a decision was made to proceed with the in-house upgrade plan. This paper will describe which MPMF subsystems were replaced and explain how the upgrades affect the performance capabilities of the system.

SYMBOLS

d	test item center of gravity location relative to table coordinate system
D	measured dynamic moment, which includes the static moment
g	acceleration of gravity
I_t	tare moment of table, fixture, etc.

I_0	moment of inertia of test item about its centroid
K	constant for torsional pendulum involving elastic characteristics of torsion rod and $(2\pi)^2$ factor
m	mass of test item
S	calculated static moment
T	period of oscillation
_	angular speed in radians/sec

OVERVIEW OF FACILITY OPERATION

The MPMF performs weight, CG, MOI, and POI measurements of items mounted to its measuring table. Weight is measured using a platform scale that the MPMF table sits on.

Center of Gravity

For CG measurements the facility measures the moment generated about a set of table coordinate axes. Measurements are typically taken at four index positions of the table, 0, 90, 180, and 270 degrees. By dividing the moment by the measured weight of the test item, the location of the CG of the test item can be calculated relative to the table coordinate system. By knowing where the test item is specifically located on the table, this measurement can be transformed to a test item's coordinate system.

Moment of Inertia

For MOI measurements a chuck is engaged at the base of the table that transforms the table into an inverted torsional pendulum. The table is given a small angular displacement, then released and allowed to oscillate. The oscillation period is measured. The MOI value is calculated from the period measurement and a torsion rod constant using equation (1).

$$I_0 = T^2 K \Box I_t \Box md^2 \qquad (1)$$

Product of Inertia

For POI measurements a motor drives the table to some specified spin rate and then the table is allowed to free spin. Measurements of the moment generated about a set of table coordinates are taken. The POI values are calculated using equation (2).

$$POI = \frac{(D \Box S)g}{\Box^2} \qquad (2)$$

OLD SYSTEM DESCRIPTION

The original MPMF consists of two main components, the table that the test items are mounted to and the measurement and control console. Figures 1 and 2 are pictures of the old system showing the table and the console. The table contains the mechanical parts of the system. These parts include the hemispherical gas bearing, the support ring, the drive motor, the chuck and chuck engagement motor, the indexing ring, the moment sensor, and the gas supply plumbing. The hemispherical gas bearing is the core of the system. The measuring table is attached to the top of the hemispherical bearing and there is a stabilizing shaft protruding down through the table from the hemispherical bearing. At the bottom of the shaft is the torsion rod that is used for MOI measurements. Figure 3 shows this central structure of the system. The support ring supports the table and anything mounted on it when the gas supply to the hemispherical bearing is turned off. The ring is lowered once gas is flowing to the bearing, allowing the measurements to be made. The drive motor is used to spin the table for POI measurements, for the other two types of measurements the table is manually positioned. The torque generated by the motor is adjustable and there is a clutch and brake mechanism on the motor. The chuck and the engagement motor are located at the base of the stabilizing shaft. When the chuck is engaged, during MOI measurements, the table is restrained from spinning. There is a gas-powered solenoid under the measuring table that is extended to give the table a consistent angular displacement of approximately 3 degrees. This solenoid is then retracted to release the table, which then oscillates. The moment sensor that measures the table imbalance is located near the bottom of the stabilizing shaft at a known distance from the pivot point of the hemispherical bearing. It is a strain gage type force transducer. The indexing ring is also located on the stabilizing shaft. It uses an array of eight LED's, photocell sensors, and concentric indexing holes in the ring to determine the angular position of the table. It is also used to determine the timing of the MOI period of oscillation and the POI spin rate. The only part of the table that was changed during the upgrade was the aluminum gas supply plumbing. It was modified to satisfy safety regulations and to further mitigate payload risk due to a facility failure.

The measurement and control console contains the components that control table functions as well as acquire and process the measurement signals from the force transducer and the indexing ring. At the console, the force transducer's bipolar output is amplified and routed to a voltage controlled oscillator (VCO) and digital counter. The VCO and counter function together as an integrating digital voltmeter. The VCO generates a signal with a frequency proportional to the output of the moment sensor. This frequency is totalized by the counter and the resultant indication is a direct measurement of the moment of the system. The output is a convenient digital indication, which has been integrated over a finite period, thereby averaging out noise. The console also contains the interlock mechanisms for the facility. It was this console that was experiencing the majority of the recent failures.

NEW SYSTEM DESCRIPTION

The old console was replaced by an in-house built chassis, see Figure 4, containing on/off power switches, solid state and mechanical relays, voltage sources, a DC motor controller, and primary and secondary GN2 status indicators. Also inside the chassis is a Pentium III desktop PC with a National Instruments 16-bit multifunction data acquisition card and a National Instruments 24-bit digital I/O card. The new hardware connects to the table using the same cables and connectors as the old console. Because of this, the system could quickly be reconfigured to operate with the old console at any time during the upgrade process. Labview is the software being used to generate the system's Graphical User Interface (GUI), monitor the system interlocks, and acquire and process the measurement data. The data acquired by the system is output in Microsoft Excel compatible format so it is easy to manipulate and generate reports. Some sample screen shots of the GUI are given in Figures 5-7. The overall software architecture is a Labview implementation of a hierarchical state machine as shown in Figure 8. Each of the three test types, CG, MOI, and POI is a state with internal sub-states. This design approach lends itself to relatively easy expansion or modification.

For CG measurements, the current procedure calls for manually spinning the table at a very small rate, less than 4 rpm. The system samples the load cell and indexing ring signals at 5000 samples/sec. As the table rotates, the system captures approximately 200 load cell data points around four index points of the table, 0, 90, 180 and 270 degrees. The average of each 200 points is calculated and the four resulting values are used to calculate the moment about each table axis, 0-180 and 90-270. This process is repeated four times as the table rotates and then the average of each moment value is calculated and displayed on the computer screen. These final values, as well as the intermediate results, are written to a Microsoft Excel compatible file.

For MOI measurements, the table oscillates about the 0 degree index. The indexing ring signal is sampled at 10,000 samples/sec. Once the table is released to oscillate, the system waits a short period of time to allow any transient motion to settle and then acquires 4 oscillations of indexing ring signals. The period of each oscillation is calculated by differencing zero crossing times. The four period values are averaged and the result is displayed on the computer screen and written to a Microsoft Excel compatible file.

For POI measurements, the operator begins by entering a target spin rate. Once the spin rate has been achieved, the clutch is disengaged and the motor is stopped to allow the table to free spin. After a short time delay to allow any transients to decay, the system acquires a full cycle (360 degrees) of load cell and indexing ring data. This data is sampled at 5000 samples/sec. The load cell data is then fit with a Fourier series whose real component is the moment about the 0-180 axis and whose imaginary component is the moment about the 90-270 axis. This process is repeated for multiple table spin rates and the complete dataset is written to a Microsoft Excel compatible file. The data can then be plotted as moment versus spin rate squared. A linear curve fit is performed on this data with the slope representing the dynamic portion of the moment and the y-intercept representing the static portion of the moment.

The aluminum gas lines were replaced with stainless steel gas lines to meet safety regulations. As part of the upgrade process a payload risk mitigation analysis was performed to determine if anything could be done to reduce the risk to the test item in the event of a MPMF failure. As a result of this analysis a secondary, backup gas supply was added to the system when the gas lines were replaced. The system is now designed to switch to the backup gas supply when it senses a disruption in the primary gas flow. This would prevent the hemispherical bearing from seating into its socket and suddenly stopping while in motion, an event that could not only damage the test item but also damage the bearing. The primary gas supply is typically house GN_2 while the backup is typically bottled GN_2, however both supplies could be bottled GN_2.

PERFORMANCE

One of the requirements of the new measurement and control system was that it must have performance characteristics as good as or better than the old system. In terms of table control, all of the functions have been replicated in the new system. One control function that has improved is the table spin drive function for POI measurements. There is now finer control over specifying and achieving a target speed for the table. As mentioned previously, the safety of the system has been improved with the addition of the backup gas supply.

In terms of the measurement functions of the table, the accuracy is dependent on the timing and moment measurements. The imbalance moment is measured using the original load cell in the table. The full-scale voltage on the 16 bit acquisition board is currently set to +/- 0.5V resulting in a voltage resolution of 15.3 _V. Combining this voltage resolution with the load cell sensitivity results in a moment signal resolution of 0.2 Nm (1.8 in-lbs.). There are two types of timing measurements made, an oscillation period for MOI measurements, and a table speed measurement for POI and CG measurements. The timing resolutions are dependent on the sampling rates, which are 5,000 samples/sec for POI and CG measurements and 10,000 samples/sec for MOI measurements, resulting in resolutions of .0002 seconds on spin rate and .0001 seconds on oscillation period.

Once the new measurement and control system was operational, a calibration of the MPMF was performed to confirm accurate operation of the facility. First, multiple measurements were taken on just the bare table to confirm the table is balanced and to confirm the factory provided values of 12.8444 for the torsion rod constant K, and 39.8868 kg-m^2 (29.41855 slug-ft^2) for the table inertia. All CG measurements were in the range of ± 0.1 Nm (±1.0 in-lb), which indicates a balanced table. The factory torsional constant was used to calculate MOI values from the measured periods. These calculated values were within ±0.01% of the factory provided table MOI value. Next, two rectangular, machined weights, one 136.98 kg (302.00 lbs.) and one 248.00 kg (546.75 lbs.), were placed on the table and pinned at specific table locations. Numerous CG and MOI measurements were taken with the calibration weights placed at various radial and angular positions on the table. The theoretical CG and MOI values can be calculated for each block at each location. The measured values can then be compared to the theoretical values. The results are summarized in Tables 1 and 2. The calibration results confirm that the new measurement and control console meets the performance specifications of the old system.

FUTURE PLANS

The upgrade process turned into a much bigger task than originally envisioned. During the process some areas were identified as needing improvement over current plans. One item was the version of Labview being used. The Labview version 5.1 Full Development System was used because a license was already in place for this software when the upgrade began. However, it was discovered that version 5.1 is not able to handle the required amount of multitasking necessary to implement the application as desired. Also, the version 5.1 Full Development System does not allow an executable version of the application to be created which would aide in the configuration management of the system. For these reasons, it is planned to upgrade to version 7.1 in the near future. Some improvements in table spin control are also planned once the Labview upgrade has been completed. In addition, the MPMF will be undergoing a test to verify its operation in a thermal vacuum chamber. This is sometimes necessary to remove the air drag on the test item when the table is spinning. The MPMF will be placed in Goddard's Space Environment Simulation (SES) chamber, taken to a pressure of 1-5 Torr, and the system operated in POI and CG mode.

CONCLUSION

An upgrade has been performed on the Goddard Space Flight Center's Mass Properties Measuring Facility. The upgrade has been shown to improve both the performance and the reliability of the measuring and control system of the facility. These modifications will allow the facility to continue to be used for many years.

	Calibration Weight Location		Maximum Difference Between Theoretical and Measured CG		Minimum Difference Between Theoretical and Measured CG	
Weight (kg)	Radius (m)	Angle (degrees)	Radius (m)	Angle (degrees)	Radius (m)	Angle (degrees)
136.98	.10	0	.01	.34	.01	.15
136.98	.25	180	.04	.03	.04	.02
136.98	.41	0	.10	.11	.09	.08
248.00	.10	180	.02	.28	.01	.06
248.00	.25	90	.11	.05	0.00	.04

Table 1. New System's CG Performance Summary

	Calibration Weight Location		Maximum % Difference Between Theoretical and Measured MOI	Minimum % Difference Between Theoretical and Measured MOI
Weight (kg)	Radius (m)	Angle (degrees)	(%)	(%)
136.98	.10	0	.29	.10
136.98	.25	180	.39	.37
136.98	.41	0	.12	.07
248.00	.10	180	.43	.39
248.00	.10	90	.46	.40
248.00	.10	0	.60	.54

Table 2. New System's MOI Performance Summary

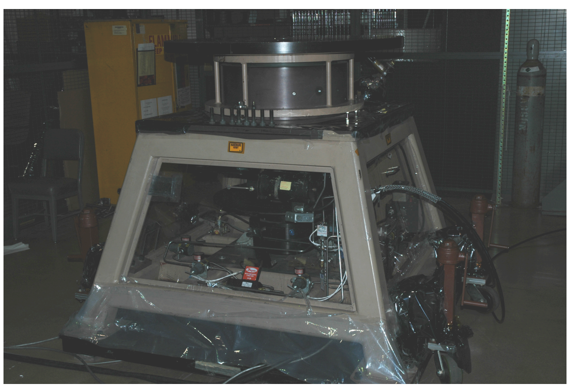

Figure 1. MPMF Table

Figure 2. MPMF Old Console

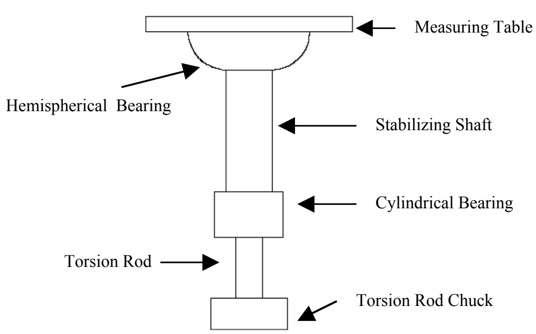

Figure 3. MPMF Table Inner Structure

Figure 4. MPMF New Console

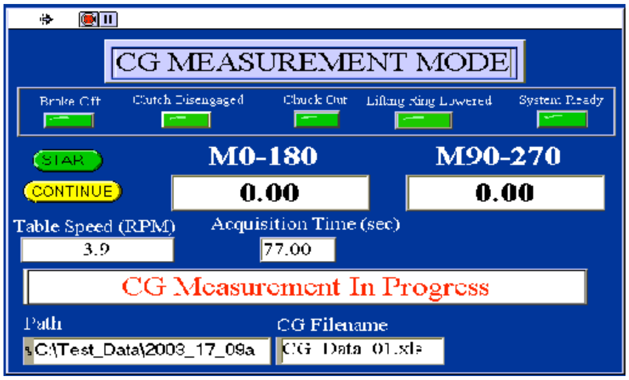

Figure 5. GUI for CG Measurement Mode

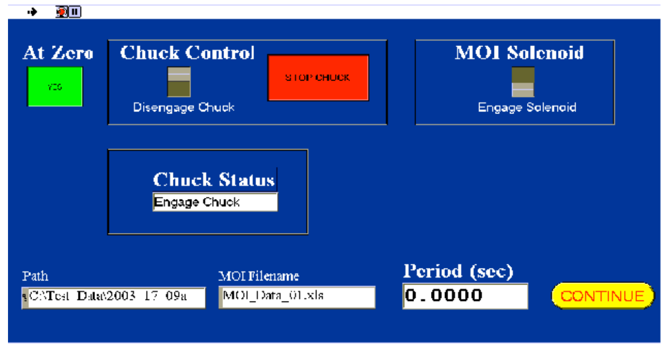

Figure 6. GUI for MOI Measurement Mode

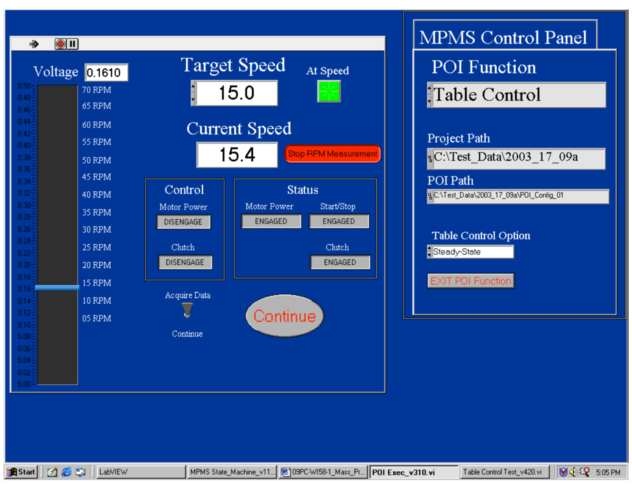

Figure 7. GUI for POI Measurement Mode

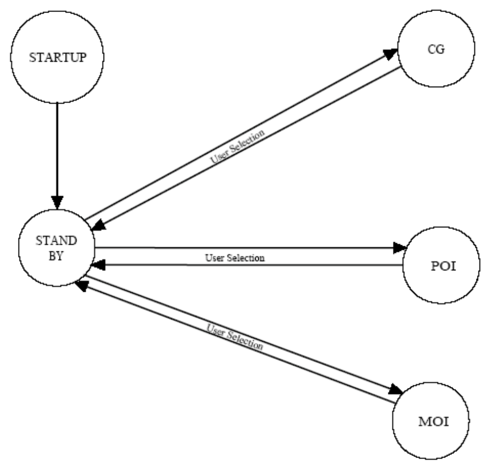

Figure 8. New System's State Machine Design

Home Paper Abstract

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Facility Before

- Mass Properties Measuring Facility (MPMF) measures weight, cg, MOI, and POI

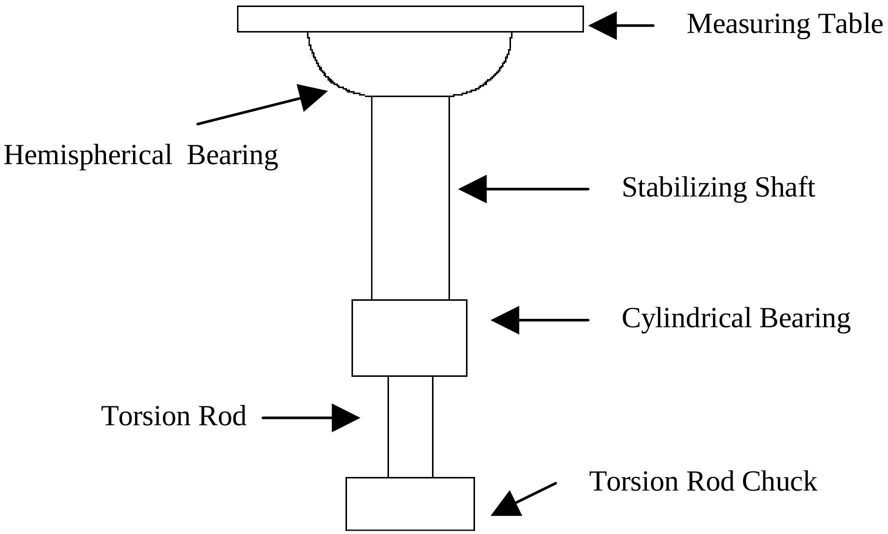
Maintenance Issues

- Measurement and control console experiencing more frequent failures
- Many parts use antiquated relay technology and replacement parts are not available
- System sometimes gets shipped to other locations and reliability is critical

Upgrade Options

- Contract Out
  - Proposal was to replace hemispherical gas bearing and drive motor with an integral bearing and motor assembly as well as measurement and control functions
  - $178,000 and facility unavailable for 3-6 months
- In-house
  - Proposal was to leave mechanical table in tact and replace measurement and control console
  - $81,000 and facility unavailable for 1-2 weeks to replace gas line plumbing
    - Have ability to switch back to old system at any time

Table Components



Old Console Components

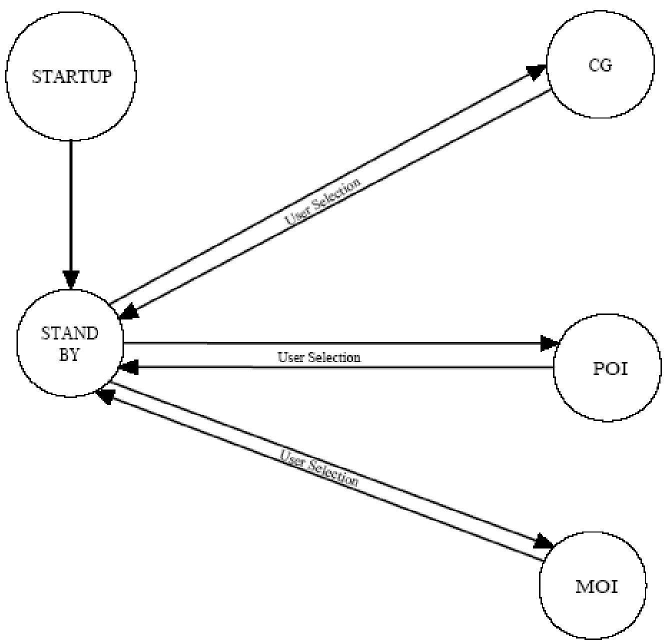
- Measurement display and control functions
- Voltage Controlled Oscillator and Digital Counter used to display moment
- System interlocks

New Console

- Pentium III PC
- NI 16-bit multifunction data acquisition card
- NI 24-bit digital I/O card
- Labview software
- Uses same cables to connect to table as old console

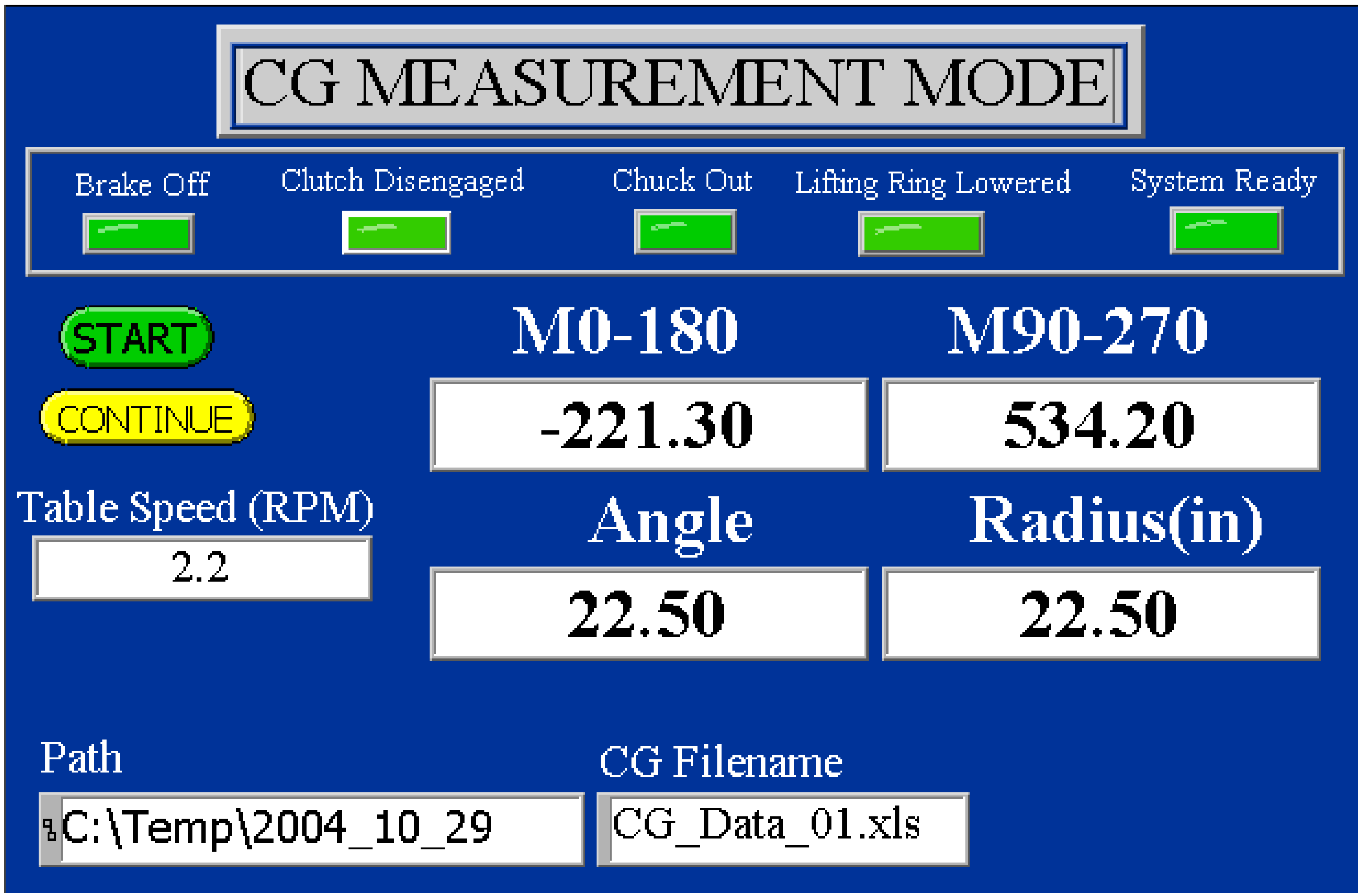
New Console

- Labview Used to:
  - Generate GUI
  - Monitor interlocks
  - Acquire and process measurements
- Architecture is implementation of hierarchical state machine
- Acquired data is output to Excel compatible file



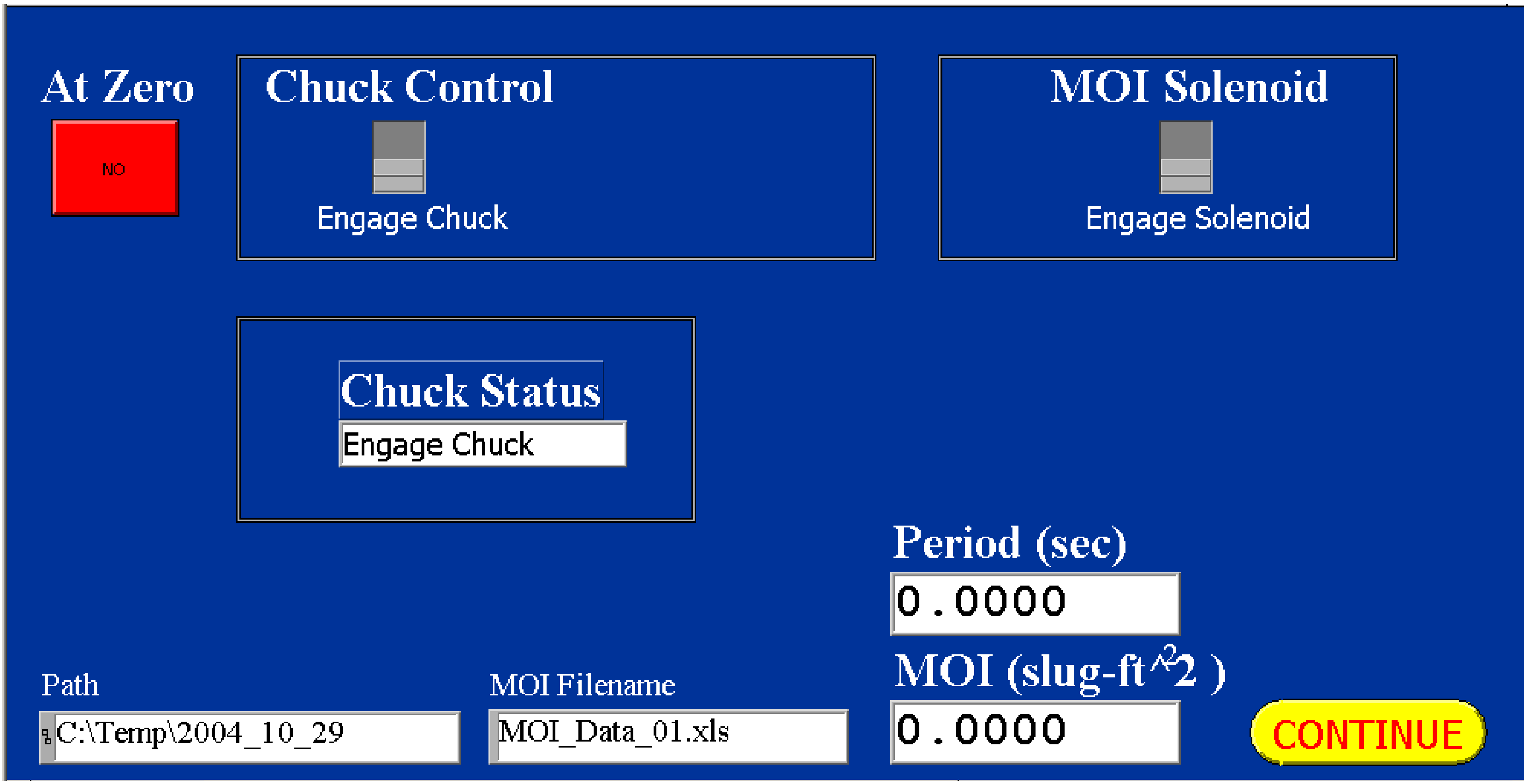
GUI Display

CG Mode



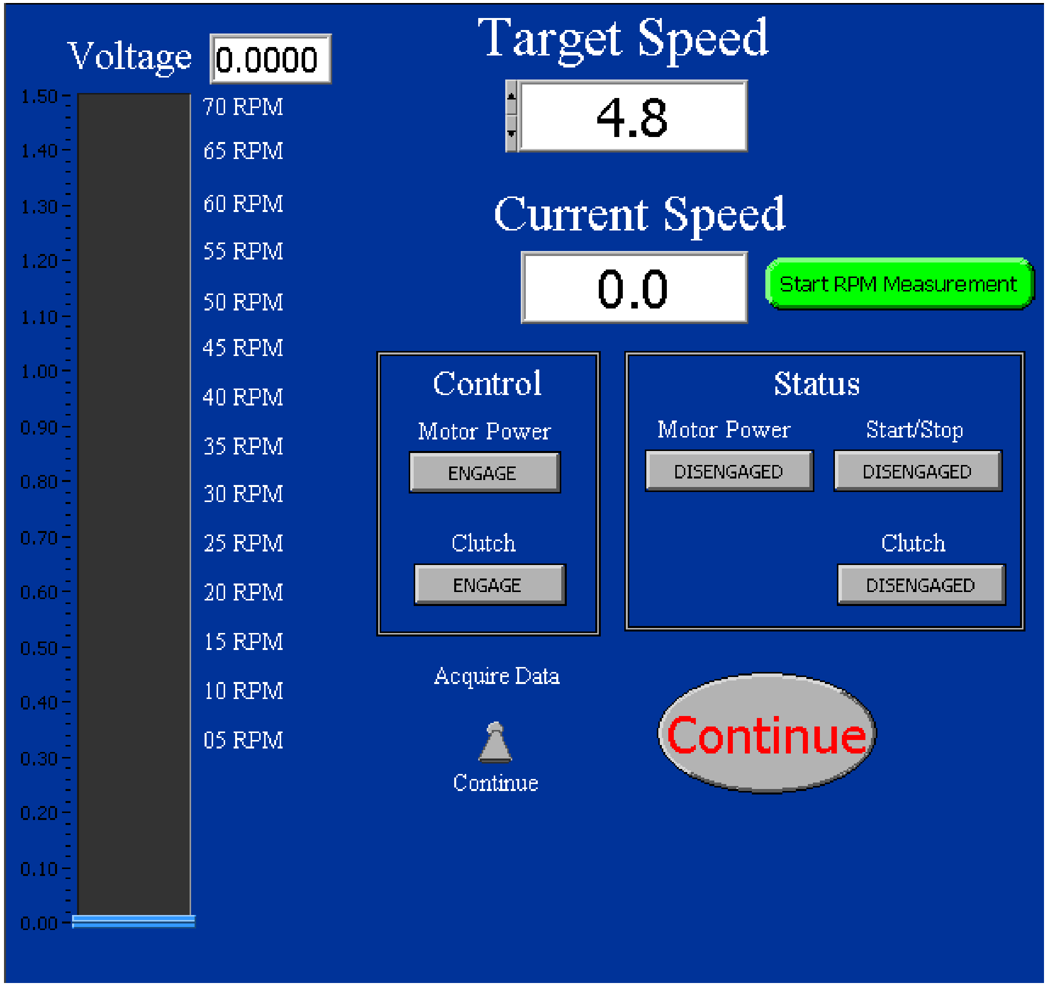
GUI Display

MOI Mode



GUI Display

POI Control Mode



Safety Upgrades

- Aluminum gas lines replaced with stainless steel
- Secondary, backup gas supply added to system
  - System switches to backup supply when disruption in primary flow is sensed
  - Prevents gas bearing from suddenly stopping and seating in socket
    - This event could damage both the test item and the bearing

New System Performance

- Control functions replicated
  - Table spin control easier to specify target speed
- Measurement accuracy dependent on timing and moment measurements
  - Moment resolution .2 N-m (2 in-lb)
  - MOI period resolution .0001 second
  - POI spin rate resolution .0002 second

Calibration Results

- Multiple measurements taken on bare table
  - Confirm table balanced
  - Confirm factory supplied values for table inertia (39.8868 kg-m$^{2)}$ and torsion rod constant (12.8444)
- All cg moment measurements in range of ±0.1 Nm (1.0 in lb)
- Using factory torsion rod constant, table inertia values within ± 0.01% of factory supplied table inertia value

Calibration Results

- Used 2 machined weights to perform calibration
  - 137 kg and 248 kg (~300 lb and ~550 lb)
- Pinned weights at various locations on table
- Numerous cg and MOI measurements taken
- Theoretical cg and MOI values calculated for each position
- Results show new system performance meets the old system specifications

Calibration Results

	Calibration Weight Location		Maximum Difference Between Theoretical and Measured CG		Minimum Difference Between Theoretical and Measured CG	
Weight (kg)	**Radius (m)**	**Angle (degrees)**	**Radius (mm)**	**Angle (degrees)**	**Radius (mm)**	**Angle (degrees)**
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136.98	0.25	180	1.0	0.03	1.0	0.02
136.98	0.41	0	2.5	0.11	2.3	0.08
248.0	0.10	180	0.5	0.28	0.25	0.06
248.0	0.25	90	2.8	0.05	0.0	0.04

Calibration Results

	Calibration Weight Location		Maximum % Difference Between Theoretical and Measured MOI	Minimum % Difference Between Theoretical and Measured MOI
Weight (kg)	**Radius (m)**	**Angle (degrees)**	**(%)**	**(%)**
136.98	0.10	0	0.29	0.10
136.98	0.25	180	0.39	0.37
136.98	0.41	0	0.12	0.07
248.0	0.10	180	0.43	0.39
248.0	0.10	90	0.46	0.40
248.0	0.10	0	0.60	0.54

Future Plans

- Upgrade Labview software
  - Better handle multitasking
  - Help with configuration management
- Improvements in table spin control
- Planning to put table in T/V chamber to verify its operation in vacuum