Individual Component Analysis

Team 24 - Resistive Force Measurement Apparatus
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Project Introduction:

The goal of this project is to create a device to measure the resistive torques and forces of a physical intruder moving through sand and other granular media (GM). Commissioned by the Office of Naval Research, Drs. Gravish and Tolley have studied and produced robots capable of moving through sand via “swimming” motions, with the long term goal of manufacturing bio-inspired robots that can traverse through open water and shallow sand environments. In order to achieve this, an accurate understanding of the resistive forces that a robot experiences in various sand types is needed. To do this, the team will create a device that can quickly characterize the torques and forces experienced by a body moving through GM.

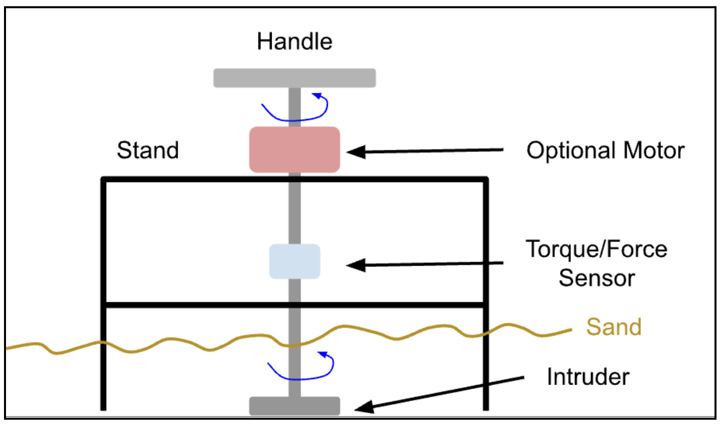


Figure 1: Concept sketch from sponsor specifications (from sponsor presentation)

The main functional requirement of the apparatus is to measure intruder angle and torque vs time, in order to categorize the torque vs both angular displacement and velocity. The apparatus must be able to make measurements quickly to allow for the characterization of many sand conditions by a team of two or fewer people. Categorization is intended for many sand conditions, including variation in sand type, compact level, moisture content, and temperature. This will include measurement in partially submerged conditions, and up to a depth of 10 inches (25 cm). Other functional goals include the ability to record vertical force data, sand conditions (as mentioned above), and GPS location.
The primary constraints of the project include factors such as setup time, transportation, and budget. While a lead time of up to an hour for setting up the device is acceptable, each measurement should not take more than five minutes. Further, the device must be able to be transported within a standard sized car or sedan. Finally, the budget for components and materials is $1000, but this may be negotiated depending on project needs.

Component Introduction:

To create this device, force and torque sensing equipment will be required to make the measurements necessary for the goal of the project. Sensors will have to produce accurate measurements within the range of loads experienced within GM. The primary goal of the project is categorizing the horizontal loads experienced, which are quantified using the torque on the rotating intruder. However, vertical load sensing may also be included, as the movement of an intruder through GM creates “buoyant”-like forces due to the pressure difference between the sand in contact with the top and bottom of the intruder. This produces a lifting force on the intruder; however this is not a high priority for the project, and may not be measured in the final design. Both forces and torques will be measured in the up direction relative to earth’s fixed frame.

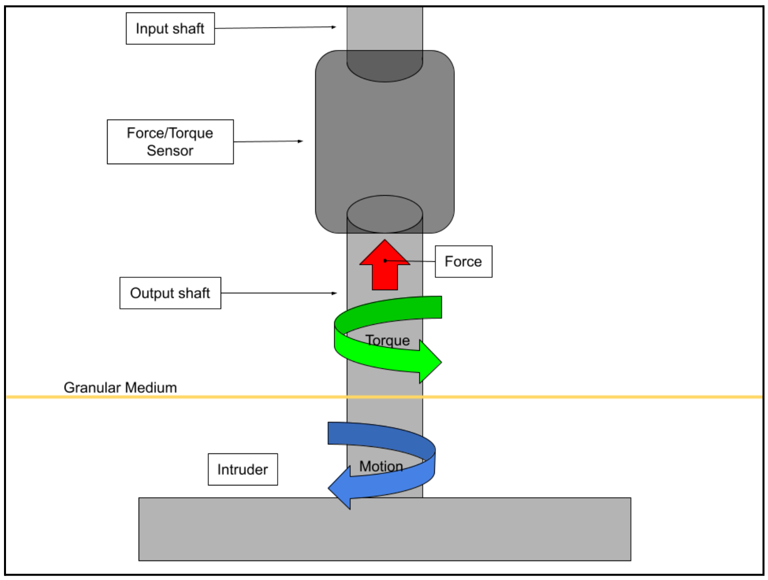


Figure 2: Drawing of intruder mechanism, indicating motion and the forces and torques to be measured. Input and output shafts are connected rigidly but pass through a Force/Torque sensor system. Force and torque sensors are not necessarily combined. Shaft and intruder not shown to scale. Bushings and apparatus structure not shown.

Although the exact range of loads expected is not currently known, the torque is expected to be in the range of 1-100 Nm. The lifting forces are less well defined, but being able to measure between 1-100 N should be sufficient.

The main functional requirement of this sensor system is the ability to measure horizontal loads (torques) on the intruder over time, with the secondary goal to measure vertical loads. This is constrained by the necessity for this sensor system to be sand- and water-proofed, and an ability to integrate this with the electrical and data storage system the team uses for the apparatus. Further, measurements must be possible on a moving intruder bar, as load sensing will be performed at various sand depths. The project has a total material and component budget of $1000.

Proposed Solutions:

There are two categories for possible solutions for force/torque sensing equipment; the sensor can either be purchased Off the Shelf (OTS) from a retailer or made in house using calibrated parts and strain gages.

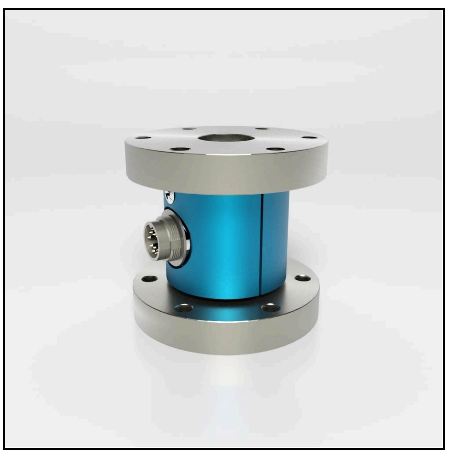
Options for OTS components:

McMaster-Carr Inline Shaft Torque Sensor:

This torque sensor is mounted between two shafts with four threaded holes on each mounting face. This sensor is designed to "measure and record manually applied torque", as would be transmitted through manual operation or non-impact power tools. This sensor outputs an electrical signal based on the torque it measures, which can be interpreted to produce a measurement of torque vs time. This sensor is manufactured with a range of load capacities, ranging from 6 Nm to 150 Nm.

Figure 3: Image of McMaster-Carr Torque Sensor 7570N13 (via McMaster-Carr).

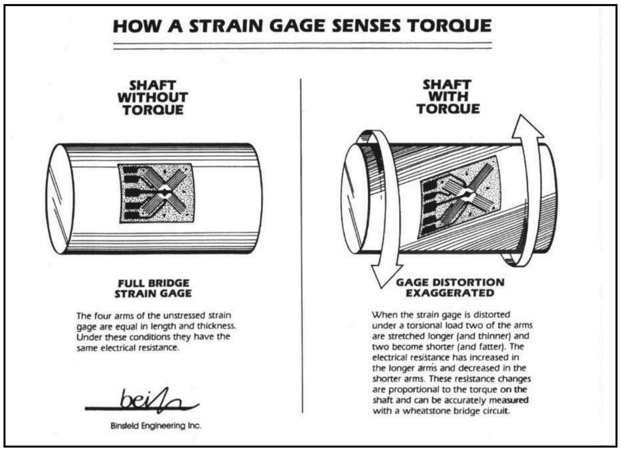
Interface Force Measurement Solutions Axial Torsion Load Cell:



This combined force torque sensor is mounted between two shafts with six threaded holes on each mounting face. This sensor measures both axial torques and forces, and transmits these data through electrical signals, which can be interpreted to produce force and torque signals vs time. This sensor is manufactured with a broad range of load capacity options, ranging from 5 Nm to 50 Nm of torque.

Figure 4: Image of Interface Solutions AT101 2-Axis Axial Torsion Load Cell (via Interface Force Measurement Solutions).

Options for In-House Solutions:
Strain Gage Torque Sensor:



A strain gage works by varying the amount of resistance it generates based on the amount it is stretched (strained) in a particular axis. By placing multiple gages on the surface of a shaft oriented in a pattern in line with the torque axis, these gages can be used to measure the amount of shear strain experienced at the surface of the shaft. With knowledge of the length, cross-section, and material of the shaft, the torque can be determined.

Figure 5: Diagram of a strain gage system designed to measure shaft torque.

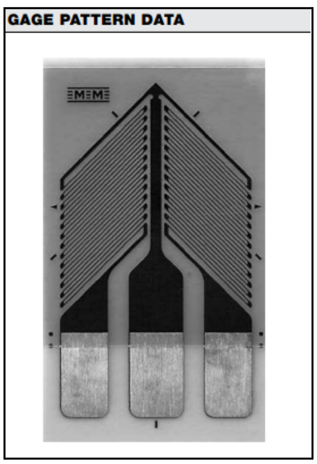
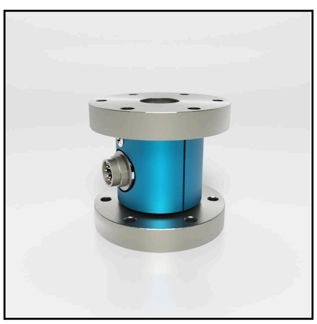
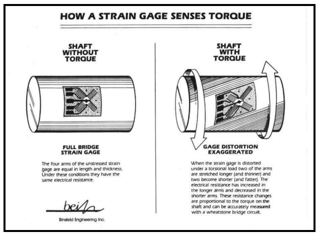


Figure 6: Pattern for a strain gage designed to be implemented into a shaft torque measurement design (via Micro Measurements).

Design Solution Name	Pros	Cons	Price (EA)
McMaster-Carr Inline Shaft Torque Sensor 	- Sold by a reputable brand with reliable customer service and fast shipment. - Known specifications, mounting sheets, and other documentation. - Strong under axial forces, unlikely to fail under high loads or impact (has overload protection). - Built in wiring and communication systems. - Multiple force capacity options based on project needs; sensor capacity between 6-150 Nm (max torque). Lower load capacity will produce greater measurement precision	- Does not contain axial force measurement capabilities. - Higher cost than desired for the budget of this component of the project. With a total budget of only $1000 for parts and components, this may be outside of the project budget. - Inability to change measurement configuration once purchased; if one measurement range does not work, we will not have the budget to purchase another sensor.	**$684.29** Shipping time: 2-4 weeks
Interface Force Measurement Solutions Axial Torsion Load Cell 	- Greatest range of measurement capability. Is able to measure both axial torques and forces, allowing us to fully realize the goal of the project. - Greatest mounting flexibility. Large flanged base with numerous mounting locations allows for multiple mounting configurations. - Greatest resistance to shock and load; unlikely to fail given conditions.	- Unattainable budget range. This price tag was only determined after research on this had already been performed and heavily considered (included in this report primarily for documentation purposes). - Does not include wiring with purchase, must create or purchase separate signal transmission cables.	Starts at **$4864.50** Shipping time: 1-3 weeks
In House Strain Gage Torque Sensor	- Greatest flexibility in terms of measurement range and precision. Team has ability to change the maximum and minimum torque by changing the component geometry without altering	- Requires most time and research commitment to create useful measurement capabilities. This solution is not guaranteed to work (**greatest risk**) - Having a precise	Price per strain gage: **$202.73** Stock and other components: **~$100** Total:

	the gages needed. - Least expensive option by far. Allows team ability to experiment with multiple options without exceeding project budget.	enough sensor will require a large ratio of shaft circumference to the second moment of area and material strength. Low strength and cross section under moderate load will reduce structural rigidity and may lead to sensor failure. - This solution is least likely to succeed in corrosive and wet environments, as it involves adhesive strain gages which are likely to fail under these conditions.	**~$500** Shipping time: not applicable, design will take anywhere from 3-8 weeks.

Project Impact:

The decision regarding which sensor solution to pursue will likely be the most significant decision of the project, as this component will likely consume a large portion of the team's time and budget over the project timeline. While an OTS component will save time, it will cost a large part of the team's budget and will decrease the team's ability to experiment with other design solutions in other parts of the project. Conversely, an in-house component will be less expensive, but will consume much of the team's design period.

Other design solutions are still being proposed and considered by the team and their sponsors. This decision will be of great significance throughout the project and will likely dictate the course of the project as a whole.

This decision will also directly interact with other components of the project. An in-house sensor will be larger, and thus will affect the positioning of other components within the apparatus structure. It will also have to have more care taken to isolate it from the elements, as the adhesive will be prone to disconnecting from the measurement shaft. OTS sensors will also require integration with the rest of the electronics package.

Appendix:

Research references:

McClements, D. (2023, March 23). Shear Modulus: Definition, Values, and Examples. www.xometry.com. https://www.xometry.com/resources/3d-printing/what-is-shear-modulus/

- Provided insight to the use of shear stress and strain in torque measurement. Provided shear modulus for various materials to inform decision on ability to create in-house torque sensor.

Binsfield Engineering (2019, December 27). What is a Strain Gage and How Does It Work? Binsfeld. https://binsfeld.com/what-is-a-strain-gage-and-how-does-it-work/

- Informed discussion of strain gages and implementation of strain gages in force/torque measurement.

Perry, C. C. (1969). Plane-shear measurement with strain gages. Experimental Mechanics, 9(1), 19N22N. https://intertechnology.com/Vishay/pdfs/TechNotes_TechTips/TN-512.pdf

- Research paper providing application references of how to create torque sensors from strain gages. Gave insight as to Wheatstone Bridge applications and necessity of multiple strain gages.

Products researched:

McMaster-Carr Torque Sensor:
Link: https://www.mcmaster.com/7570n13/
Search term: (Mc-Master Carr) Torque Sensor
Product Name: Torque Sensor (0.1 NM to 60 NM)
Product Number: 7570N13

Interface Measurement Solutions Force/Torque Sensor:
Link:
https://www.interfaceforce.com/products/multi-axis-sensors/2-axis/at101-2-axis-axial-torsion-load-cell/
Search term: (Google) Axial Force and Torque Sensor
Product Name: 2-Axis Axial Torsion Load Cell
Product Number: AT101
Spec Sheet: https://www.interfaceforce.com/wp-content/uploads/AT101-DS-1.pdf

Vishay Precision Group Micro Measurements Shear/Torque Strain Gage:
Link:
https://www.digikey.com/en/products/detail/micro-measurements-division-of-vishay-precision-group/MMF404956/2503699
Search term: (Digikey) Strain gages, Shear/Torque pattern type
Product Name: General Purpose Strain Gage—Shear/ Torque Pattern
Product Number: MMF404956
Spec Sheet: https://docs.micro-measurements.com/?id=2555

Notes:
Call made to receive quote for Interface Measurement Solutions Force/Torque Sensor.

- Brief discussion with Lee from Interface Force Measurement Solutions
- Multiple product versions described with various load capacities discussed
- Quote received at two price points
    - 0.5kN and 5Nm, 1kN and 30 Nm, 2kN and 50Nm: $5865
    - 1kN and 10Nm, 2kN 30Nm: $5405
- Pricing offered at a 10% discount for education use
- Brief discussion about alternative sensors from their catalog but all were outside of the budget of the project