Semester project report

Design and Integration of a Multi-Axis Force/Moment Sensor for the Roombots

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Abstract

Roombots are modular robots developed at Biorob, EPFL, to build reconfigurable structures and to investigate distributed locomotion.

In this semester project, we designed a force/moment sensor based on strain gauges that is integrable in the Roombot modules to enable a better control of their displacements. This sensor can for example detect collisions between modules during reconfiguration or contact with the ground during locomotion, and can tell in which direction the contact is and what is the intensity of the applied force.

We started by designing several models in simulation and then implemented the most promising one for real.
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Chapter 1

Introduction

In this chapter, we present the context of the project and its objectives.

1.1 Force sensing for robots

In robotics, force and moment sensing is useful for various purposes. It is most often used in the control loop of manipulators, or in legged locomotion. In those applications, the sensors are usually placed at the hand or foot level. Another application of force and moment sensing is security or compliance. In this case, the sensors are rather placed closer to the base of the limbs, to be able to monitor forces applied at any location. A more exotic and recent application of force and moment sensing is machine learning [5].

1.2 Roombots

Roombots [3] are modular robots that are being developed at BioRob. Figure 1.1 shows a Roombot module.

They are designed for two main research tasks. The first one is to serve as building blocks for self assembly and reconfiguration of static structures such as intelligent furniture. The second task is to serve as a platform for research on distributed locomotion, especially based on central pattern generators (CPGs).

The main characteristics of the Roombots are:

- homogeneous modules
- autonomous modules
- 3 degrees of freedom
- 10 active retractable connectors by module
- size: 110 x 110 x 220 mm
• weight: 1.4 kg

Both the tasks the Roombots are designed for would benefit greatly from information about forces and moments applied to the modules. For the reconfiguration task, it would allow the modules to get into position easier by detecting contacts between modules. For the locomotion task, it would detect the contact with the ground and could be used to close a control loop.

1.3 Objectives of the project

Here are the objectives of the project as they were decided at the beginning:

This semester project has the goal to design and integrate a multi-axes force sensor (3-axis or 6-axis) into the outer, main joints of Roombots.

The work should be carefully structured and ordered, and would involve at least the following steps:

1. Gantt chart with tasks, time limits, and milestones. There will be a mid-defense and a final defense (both orally).
2. A short introduction on the background of single axis and multi-axes force measurement. (materials, physics and mechanics, theory, implementation examples, applications, key features, typical electronics, key words...).
3. Above introduction has to be based on an extensive literature research.
4. Research for producers of strain gauges of different types, and producers for related equipment. Select off-the-shelf parts for purchase.
5. Propose multiple, different designs for the force sensor for a Roombot double-hemisphere (e.g. placement of the strained structure within the module, type of strained structure…).

6. Select the most promising solution (availability, sensitivity, implementation space, cross talk, price, robustness, applicability…). Propose an appropriate list of selection criteria.

7. Design the chosen solution.

8. Electronics implementation (with help from e.g. Rico Moeckel).

9. Finite element analysis (FEA) of the force measuring structure in e.g. Solidworks FEA, Ansys or a similar software.

10. Possibly return to re-design the structure. Repeat cycle until an appropriate design is available.

11. Produce drawings, implementation.

12. Characterization of the properties of the implemented solution by testing, possibly produce testing setup.

13. Documentation as: report, videos on the personal BioRob web page, digital material on CD or DVD.

We will go through these objectives along the report. Points 2 to 4 will be covered in chapter 2, points 5 to 11 in chapter 3, and point 12 in chapter 4.

1.4 Gantt chart

Here is the Gantt chart for the project as it was defined in the first weeks:

![Gantt chart]

Figure 1.2: Gantt chart
Chapter 2

Background

This chapter gives an overview of the current state of the technologies we used in the project, and a brief theoretical background needed to understand them. It also presents some examples of existing force/moment sensors.

2.1 Contact detection techniques

Several technologies are available for contact detection and could have been implemented on the Roombots. However, many of them, like optical proximity sensors or bumpers for example, cannot cover the full body of the robots. For the Roombots, which are very mobile and can turn in every direction, we really want to be able to detect omnidirectional contacts.

In addition, we also want to have an idea of the intensity of the force applied by this contact. This leads us in the choice of designing a multi-axis force/moment sensor (often called load cell) based on strain gauges.

2.2 Strain gauge technology

Most of the information of this section come from [1].

2.2.1 Principle

A strain gauge is a sensor designed to measure the strain in an object. Based on this measurement and assuming the characteristics of the material is known, one can find the corresponding stress inside the object using Hook’s law, and then based on its geometry, compute the force applied to it using structure mechanics. Strain gauges are the sensing components of load cells.

Strain gauge technology is based on the piezo-resistivity of conductors or semiconductors, i.e the change of their resistivity with strain. This change in resistivity is due to two different factors.
1. The geometric change due to the strain.

2. The change in resistivity of the material with strain.

Those two factors yield a linear relation (in the elastic domain) between the change in resistivity and the strain:

\[ \frac{\Delta R}{R} = K \epsilon \]  

(2.1)

Where \( \epsilon \) is the strain and \( K \) is the gauge factor.

This resistance change is then measured by an electronic circuit as explained later.

### 2.2.2 Strain gauge types

There are two main types of strain gauges:

**Foil strain gauges** are made of a thin conductor foil that has been etched by photolithography in a grid pattern (fig. 2.1). This pattern allows a long conducting wire to be contained in a small area. The length of the unfolded wire does not change the gauge factor but increases the gauge nominal resistance. This is useful to make sure parasite resistances are negligible and allows a higher voltage to be used in the electronics, yielding a higher signal. The conductor foil is backed with a resistive resin, which holds it together and isolates it.

Foil strain gauges gauge factor depends mainly on the geometry change due to strain and its value is around 2 for most conductors used for strain gauges.

![Figure 2.1: Foil strain gauge](image)

**Semiconductor strain gauges** use a semiconductor material (mainly silicon) instead of a conductor (fig. 2.2). Unlike foil strain gauges, semiconductor ones are often bare rather that coated in epoxy. This is possible because semiconductor gauges are made of thin strips of silicon rather than a grid structure. They work the same way as foil strain gauges but their piezo-resistivity is mostly due to change in resistivity. This change in resistivity occurs because the mobility and the number of charge carriers inside the semiconductor change when
stress is applied. They have much higher gauge factors (more than 50 times higher than foil gauges), but are a bit non-linear.

By selecting the dopant type and level and the crystallographic orientation of the semiconductor, the magnitude and sign of the gauge factor can be chosen. For P-type silicon, gauge factors vary between +100 and +175, and for N-type it varies between -100 and -140. Another advantage of semiconductor strain gauges is that they have a higher fatigue life.

![Figure 2.2: Semiconductor strain gauge [8]](image)

However, semiconductor strain gauges also have some drawbacks. One is that their change in resistivity is not exactly linear with strain. However, it can usually be neglected for small strain measurements. Non-linearity is lower in highly doped semiconductors. Another drawback is that they are harder to install than foil strain gauges. And they are also more expensive.

**Other types of strain gauges** exist but they are rarely used. One can find capacitive strain gauges, which use the geometric change due to stress to change the distance between capacitive plates, or vibrating wire strain gauges, which measure the frequency of a vibrating wire to find the stress in the wire.

### 2.2.3 Bonding

In order to measure the strain in a structure, the strain gauge must be bonded to its surface. This is done using an appropriate adhesive. Strain gauge manufacturers usually recommend the use of a specific adhesive, or provide one.

The strain is transmitted from the surface of the object to the conductor grid or semiconductor through the adhesive and the backing resin (if there is one). Therefore, the adhesive and the resin must have good characteristics to transmit the strain reliably.

The first step of the bonding process is the surface preparation. The surface receiving the gauge must be degreased, neutralized, and can be abraded for better results. Then the adhesive must be applied to the surface and the gauge must be placed and held in position with some pressure so that a thin film of adhesive will form under the gauge.

Some adhesive, such as cyanoacrylate, harden very fast (a few minutes), and the gauge can be simply held in position by thumb pressure. Unfortunately,
cyanoacrylate should not be used for long-term installations because moisture absorption will lead to a deterioration of the bond. Other adhesive such as epoxies need several hours to cure, and the gauge must be held in position using clamps. Some epoxies will cure at ambient temperature, and other need to be cured in an oven. Hot cure epoxies have better characteristics than cold cure ones, especially regarding the range of temperature in which they remain stable.

Bare semiconductor gauges require an additional step in the bounding process: the surface must be precoated with a layer of strain gauge adhesive to make an insulating layer.

2.2.4 Electronics

To convert the variation of the strain gauge in a voltage signal, one can use a Wheatstone bridge (fig. 2.3). This is the general equation for this circuit:

\[ V_{\text{out}} = V_{\text{in}} \left( \frac{R_2}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) \]

(2.2)

![Figure 2.3: Wheatstone bridge (picture from Wikipedia)](image)

This means that if all the resistances are balanced, the output voltage is zero.

Different circuit configurations have different benefits and drawbacks.

The quarter bridge configuration is the simplest one and uses only one strain gauge. The major drawback here is that the output is non-linear with the variation of resistance of the strain gauge. However, the non-linearity can be neglected for small deformations. With \( R_1 = R_2 = R_3 = R \) simple resistors and \( R_4 = R + \Delta R \) the strain gauge, the equation is:

\[ V_{\text{out}} = V_{\text{in}} \frac{\Delta R}{4R + 2\Delta R} \approx V_{\text{in}} \frac{\Delta R}{4R} \]  

(For small \( \Delta R \)
The half bridge configuration uses two strain gauges. They are both in the same arm of the circuit and must be placed so that they experience an opposite strain (one compression and the other contraction). There are many benefits with this configuration. First, the output is linear and the sensitivity is doubled. Second, sensitivity to temperature (explained later) is compensated if both gauges have the same variation in resistance with temperature. Third, one can cancel the effect of specific stress patterns by placing the gauges at the right places. For example, if one wants to measure the bending of a beam, one should place one gauge at the top and one the bottom of the beam. When the beam bends, the effects of the two gauges will add, and when the beam is simply elongated, the effects will cancel. So this will give more accurate readings.

With \( R_1 = R_2 = R \) simple resistors, and \( R_3 = R + \Delta R \) and \( R_4 = R - \Delta R \) the two strain gauges, the equation is:

\[
V_{out} = V_{in} \frac{\Delta R}{2R}
\]  

(2.3)

The full bridge configuration uses four strain gauges. It has the same benefits that the half bridge configuration, but the sensitivity is multiplied by four. And one can select more specific stress pattern by placing the gauges.

It can be important to compensate for the lead wire resistance if the configuration is not symmetric (like in the quarter bridge). This compensation is called the three lead wires compensation.

2.2.5 Errors and uncertainties

There are two different thermal issues with strain gauges. The first one is the change of the nominal resistance of the gauge with temperature. This is due to intrinsic resistivity change in the conductor and to differential thermal expansion between the gauge and the object. This temperature sensitivity can be compensated by adjustment of different parameters of the gauge for specific materials. Self-temperature-compensated gauges are commercially available for different materials. Another way to compensate for temperature sensitivity is to use compensating gauges in half or full bridge configurations.

The second issue is the change of the gauge factor with temperature. Compensating for this problem is more difficult, but usually this effect is small enough to be neglected if the gauge is used at a relatively constant temperature.

Semiconductor strain gauges are more sensitive to temperature change than foil gauges, but the relative error is comparable because of the higher gauge factor.

Even if the gauge is supposed to be used at a constant temperature, self heating of the gauge due to the current running through it can be enough to make the thermal factors to big to be neglected. It is important to have a good heat dissipation and to make sure that the power through the gauge is not to
high. A high gauge resistance will yield less power dissipation in the gauge for a same applied voltage.

Semiconductor gauges are also sensitive to light, because it can create charge carriers when it is absorbed by the semiconductor. This can be compensated either by protecting the gauges from light, or in a half-bridge circuit the same way as the temperature sensitivity, but then the two gauges should be lighted the same way.

Hysteresis, drift, creep and fatigue are other factors that will affect the measurement. Little can be done to compensate for those factors. The selection of the right gauge for the right application is the only way to minimize those factors.

2.3 Physics of elasticity

Since we want to measure the forces and moments applied to the Roombot modules with strain gauges, it is important to have a good understanding of how strain occurs.

The information contained in this section comes mainly from [2].

2.3.1 Stress and strain

Stress is the force per unit area acting on the surface of a volume element of a solid body. It can be decomposed in the normal stress, perpendicular to the surface, and shear stress, in the plane of the surface. Normal stress can be compressive or tensile. The unit for stress is the Pascal (Pa), which is defined as one Newton of force per square meter of area.

Strain is the differential deformation of a solid body resulting from stress. For isotropic materials, a normal stress in a direction is linearly related to a strain in the same direction. We have the relation \( \sigma = E \epsilon \), where \( \sigma \) is the normal stress, \( \epsilon \) is the strain and \( E \) is the Young modulus of the material. \( \epsilon \) is the displacement of a surface along its normal axis.

A normal stress also causes a transverse strain which sign is the opposite of the stress. So a solid will elongate in the axis of a tensile stress and contract on the other axis. The transverse strain is related to the axial strain by the Poisson ratio \( \nu \): \( \epsilon_{y,z} = -\nu \epsilon_x \)

There is a similar relation for shear stress resulting in shear strain: \( \tau = G \gamma \), where \( \tau \) is the shear stress, \( \gamma \) the shear strain and \( G \) the shear modulus. This time \( \gamma \) is the displacement of a surface along a transverse axis relatively to a parallel surface.

Those relations between stress and strain are only valid in the elastic domain. For higher stresses, the material enters its plastic domain and the deformations are irreversible.
2.3.2 Beam mechanics

One structure is used very often in load-cells: the beam. Those structures are often design so that it can be considered as fixed at one end, and free at the other end. A force can be applied to the free end, creating a moment along the beam and causing it to bend.

There are then two ways of measuring stress in the beam structure.

The first way is to measure the strain due to the bending stress. This stress is due to the bending torque inside the beam following the x axis (direction of the beam). The formula is $\sigma_x = \frac{yM}{I}$, where $y$ is the distance to the middle of the beam, $M$ is the internal torque and $I$ is the moment of inertia of the cross section.

Figure 2.4: Bending stress in a beam [2]

So the stress on the top surface of a rectangular loaded beam is:

$$\sigma_x = \frac{6 \cdot (F_o \cdot (L - x) + M_o)}{B \cdot H^2}$$  \hspace{1cm} (2.4)

where $H$ is the thickness (height) of the beam, $B$ its width, $L$ its length, $F_o$ the applied force and $M_o$ the applied torque. We can see that the stress is maximal at the base of the beam. The strain distribution on the top surface and the bottom surface are anti-symmetric (fig. 2.4) and two strain gauges can be placed in a half-bridge configuration.

The second way is to measure the strain due to shear forces on the side faces. In the presence of shear forces, the principal stresses can be calculated using these formulas:
The formula for \( \sigma_x \) has already been given (equ. 2.4), and the formula for \( \tau_x \) is \( \tau_x = \frac{T S'}{I b} \), where \( T \) is the shear force, \( S \) the static moment of the partial section, \( b \) the depth of the beam and \( I \) is the moment of inertia of the cross section. For a rectangular loaded beam this gives:

\[
\tau_x = \frac{3T \left(1 - \frac{2y^2}{H^2}\right)}{2BH}
\]

where \( H \) is the height of the beam, \( B \) its depth, \( y \) the distance to the middle of the beam and \( T \) the shear force. The direction of the principal stresses is shown figure 2.5.

Figure 2.5: Principal stresses direction [2]

We can see two interesting things from those formulas. First, the principal stresses at the top and at the bottom of the beam are equal to \( \sigma_x (\tau_x = 0) \), as
we saw in the first method. Here the stress depends only on the internal torque, not on the shear force. Second, the principal stresses in the middle of the beam are equal to $\tau_x (\sigma_x = 0)$. The shear stress depends only on the shear force and not on the internal torque. This is the direction followed by the principal stresses. We can see that in order to measure the strain due to shear forces, the strain gauges must be places at the middle of the side faces of the beam with an orientation of $+45^\circ$ and $-45^\circ$.

By using those two measurements techniques and choosing the geometry of the beam, one can choose how sensitive the strain gauge will be to different force and moment components. In summary there are two major differences between the two measurements techniques:

- The shear strain depends the same way on the height and the thickness of the beam, whereas the bending strain depends more on the height than on the thickness.

- The shear strain depends on the applied force whereas the bending strain depends on the moment. Therefore the bending strain varies along the length of the beam.

### 2.3.3 Influence of the structure

The theory presented in 2.3.2 is true for free end beams. However, depending on the shape of the load-cell, the bending angle of the end of the beam can be constrained by the rest of the structure. In this situation, additional moment can be induced, and it becomes soon very difficult to use an analytical approach.

Thus, the theory can be used to gain some insight about the problem, but numerical simulation such as finite element analysis (FEA) is needed in order to get a correct idea of the behavior of the mechanical structure.

### 2.4 Multi-axis Load-cells

#### 2.4.1 Principle

A load-cell is a force/torque sensor that is composed of a mechanical structure and of strain gauges attached to it. A load-cell can be attached between two mechanical parts so that it will transmit the forces and torques from one part to the other. By measuring the strain on the load-cell, it is possible to find what forces and moments are transmitted by the load-cell.

It should also be noted that the load-cell must not represent a weak point in the mechanism in which it is used. Of course it must not break, but it should also be stiff enough to meet the mechanism requirements and to avoid resonance problems. So there is a tradeoff between the sensitivity of the load-cell and its robustness. Thinner structures will have more strain for a given force, but will break easier.
2.4.2 System matrix

In order to fully characterize the forces and moments, six strain gauges that give non-redundant information are needed. Equations can then be found relating the voltage signal of the strain gauge circuits to the three force components and three moment components either by analytical characterization of the model, finite elements methods or testing. Assuming that relations between force/moment and strain are linear, and that the relations between strain and voltage output are linear too, the load-cell system can be modeled as a matrix.

The matrix can then be inverted (assuming it has full rank, which means that the strain gauges information are not redundant) to find the force/moment components out of the voltage outputs [4]. So then we have the equation:

\[ \vec{s} = L \ast \vec{f} \]

where \( \vec{s} \) is the signals vector, \( \vec{f} \) is the forces and moments vector and \( L \) is the load cell system matrix.

The linearity of the system is a strong assumption. It simplifies things a lot, but we must be sure this assumption can be done. The relation between force/moment and strain in not a problem because it is indeed linear for small deformations in the elastic domain of the material, and the load-cells are typically used in this domain. But the relation between strain in the gauge and voltage output of the circuit can be a problem for two reasons. First, if the strain gauge is in a quarter bridge circuit, the output will be non-linear. This is a good reason for using half-bridge circuits, despite the fact that it doubles the number of strain gauges. Second, semiconductor strain gauges have a non-linear relation between strain and change in resistance. Fortunately, this non-linearity is also compensated when using a half-bridge circuit.

This means that it is usually possible to model the load-cell as a linear system but care must be taken in the design to do so. This linear model is needed to find the relation between the voltage and the force/torque components easily.

2.4.3 Diagonal systems

The load-cell system can be even simpler if its matrix is diagonal. This means that each load-cell measures only a specific component of the force/torque, and that the others are negligible. In this case less computation is needed, and also there is a very good differentiations between the force/moment components.

To get a diagonal matrix, the mechanical structure of the load-cell must be designed to reduce the cross-talk between the different force/torque components on the strain. This can be done by using structure elements that are more compliant in one direction that in the others. An additional way of reducing cross-talk is to use half or full-bridge circuits. By placing carefully the two or four gauges, contributions from other force/torque components to the strain can be cancelled.

So to obtain such diagonal systems, strain gauges should be placed where the strain caused by a specific force/torque component is high but strained caused
by the other force/torque components is low, or in pairs where cross-talk can be cancelled. And the mechanical structure should be designed to provide such places.

2.4.4 Fewer axis load-cell

Simpler load-cells can be designed with less strain gauges if we do not want to measure all the force/torque components. Care must then be taken to make sure that there are not more force/torque component acting on the outputs than the number of strain gauges, otherwise the system matrix is not square anymore and cannot be inverted to find the relation between the output and the strain.

2.4.5 Examples

Here are some examples of existing 6-axis force/torque sensors.

The first example (fig. 2.6) comes from [6]. This load cell was designed to be used in robot’s fingers for grasp and manipulation of unknown objects.

It uses parallel-plate beams. The first part in a cross shape (PPB3,4,5,6) measures Fz, Mx and My. The second part (PPB1,2) measures Fx, Fy and Mz. Each force/torque component is measured by four foil strain gauges from Micro-Measurments in a full-bridge circuit.
This mechanical structure and this placement of the strain gauges yield to a diagonal matrix of the system in theory, meaning that there is no interference from the different components of the force/torque. The results of the tests gave a maximum interference error of less than 3.93.

**The second example** (fig. 2.7) comes from [7]. This load cell was designed for general purpose force/torque measurements in industry.

It uses single plate beams. It is separated in two parts. The first one has a cross shape and measures $M_x$, $M_y$ and $F_z$. This part is very similar to the first example. The second part measures $F_x$, $F_y$ and $M_z$ and is composed of four fixed blocks, four mobile blocks and a center block to which the load is connected. This example uses full-bridges circuits too and also gives a diagonal matrix. It also uses the same foil strain gauges from Micro-Measurments.

![Second load-cell example](image-url)
The third example (fig. 2.8) is the load-cell used in the iCub project [5]. It is used at the base of the legs and the arms for control in locomotion (crawling) and active compliance.

It uses semiconductor strain gauges that are placed on the four sides of the three beams. It is used together with an electronic board called STRAIN, which gave us a first idea of what could be done for our own acquisition system. The iCub literature and website do not give more information about this load-cell, but from the strain gauges configuration we can say that the system matrix is not diagonal.

Figure 2.8: Third load-cell example [5]
Chapter 3

Design

In this chapter we describe each step of the approach we followed for the design of the force/moment sensor for the Roombots.

3.1 Initial considerations

Here is a list of the main requirements for the force/moment sensor:

- The sensor implementation should not require important parts or mechanisms of the Roombots to be redesigned, and of course the sensor must fit in the modules.

- The sensor should provide useful data for the different tasks of the Roombots.

- The sensor should not mechanically weaken the Roombots too much.

Those requirements will be discussed in detail in the following subsections, as well as the choice for the strain gauges and the material for the mechanical structure.

3.1.1 Axis definition

First we need to define a frame of reference for the forces and moments applied to the Roombot.

We define the XY plane as being parallel to the floor of the Roombot hemisphere (see fig. 3.2). The Z axis is normal to the floor, pointing in the direction of the shell of this same hemisphere.

There is no reference on the Roombot for the direction of the X and Y axes, but we can define those directions on the load cells. The load cells we designed are coplanar to the floor of the Roombot hemisphere (XY plane) and have three beams pointing to the center of the floor. The Y axis is defined as pointing in the direction of one of the beams from the center of the floor. See figure 3.3 for an illustration.
3.1.2 Sensor location

To find a suitable place for the sensor to be integrated, we first have to analyze the path that the load follows to go from one hemisphere to the other.

The hemispheres are connected by a ball bearing and by a gearbox. The gearbox transmits the Mz component, and the gearbox transmits the other components. Figure 3.1 shows a schematic of the load path.

![Figure 3.1: Path of the mechanical load between the two hemispheres [3]](image)

Here is a list of the different parts that could have been sensorized with the pros and cons. The part number refers to figure 3.2.

- Part 56 transmits Mz but carries electronic circuits, and should probably not be touched.
- Part 1 transmits Mz in its upper part, and also the other components at its base. It is a simple ball bearing holder and could be redesigned as part of the sensor for Mz. The other components only act at the base and it would be hard to measure them here.
- Part 44 is the floor of the hemisphere. It transmits all the components of the load and does not carry anything yet. This looks like a good place to put the sensor.
- Part 2 is the shell of the module. It transmits all the components of the load but is a complex structure. Redesigning the shell should be avoided if possible.
The other hemisphere looks less interesting. The fact that the motor is not placed in the middle breaks the symmetry, which is bad for a load cell.

Taking all those considerations in account, we decided to focus our work on part 44 and part 1 if needed.

3.1.3 Needed data

The two main tasks of the Roombots is the assembly of structures of the day-to-day environment with reconfiguration capabilities, and the use as building block for locomotion with modular robots using central pattern generators.

In those two tasks, it is very useful to detect collisions or contacts of the modules with other modules or with the environment. It is also useful to know in which direction is the contact. Therefore Fx, Fy and Fz should be known. Fx and Fy could also be replaced by Mx and My, providing the same kind of information about the direction of the contact but in a different way.

Having both torques and forces in x and y provides information about the position of the contact and its intensity. It has been decided that this information is not critical for the tasks of the Roombots, thus allowing a cheaper, less complex and less cumbersome design.

Mz should also be measured as it represents the torque provided by the motor. This is useful information for control.

So in the end we decided that we need a 4-axis load cell measuring Fz, Mz, either Mx or Fx, and either My or Fy.
Since we will not measure all the force/moment components, the load-cell will have to be design so that the unmeasured components do not affect the other measurements.

3.1.4 Mechanical resistance

In a load-cell, the more strain there is, the larger the output signal. And the signal from a strain gauge is typically very small, so we need it to experience as much strain as possible when the load cell is used in normal conditions to get a good signal to noise ratio.

But every material has a strain limit, after which it enters its plastic domain and eventually breaks. This is true both for the mechanical structure and the strain gauge itself. So there is a tradeoff between mechanical robustness and sensitivity.

The loads applied to the Roombots in normal use must be investigated to size the sensor.

For Mz, the working torque is 7.4 Nm and the theoretical stall torque is 24.5 Nm.

For Mx and My, a normal load can be considered as two modules stretched horizontally. The torque on the first hemisphere would be 5Nm knowing that a sphere (half a module) weights 0.75kg and the distance between two spheres is 0.11m.

For Fx, Fy and Fz, different structures can be considered. For example a stool structure has eight modules and four contact points yielding to a load of 30N on each foot. A quadruped structure has five modules and only two contact points when walking, yielding to a load of 37.5N on each foot.

We decided to consider a working load of 25Nm for Mz, 5Nm for Mx and My, and 50N for Fx, Fy and Fz. The load-cell is then designed with a safety factor of five to take shocks and moderate misuse in account.

3.1.5 Strain gauges

We decided to use semiconductor strain gauges to benefit from a high gauge factor. The drawbacks from those gauges such as the higher price and the small non-linearity where not our first concern. We where more concerned by having a signal as high as possible because we thought it would be delicate to handle signals of a few millivolts.

We choose the same kind of strain gauges from Micro-Instruments that what is used for the iCub force/moment sensor, because they can be bought in matching pairs which have the same thermal sensitivity and which can be used in half or full Wheatstone bridges to compensate this effect.

Also they are very small so we thought it would allow us to design a light sensor.
The characteristics of the chosen strain gauges are the following:\(^1\):

- Product name: Semiconductor "U" Gage SS-037-022-500PU-S2
- Nominal resistance: $540 \pm 50\Omega$
- Gauge factor: $150 \pm 10$
- Size: $0.037 \times 0.016 \times 0.0004$ inches
- Price: $11.48$ for a single one, $42.99$ for a matching pair

We can see that the resistance nominal resistance and the gauge factor can vary quite a lot between two gauges, but this should not be a problem because of the possibility of buying matching pairs.

### 3.1.6 Mechanical structure material

The material for the mechanical structure had to be decided early in the design. The requirements for the material where to be light, and to have a high maximal elastic deformability, but to be stiff enough at the same time. The maximal elastic deformability corresponds to the yield strength of the material divided by its Young modulus.

We asked in the mechanical workshops at EPFL which material they had that would fill those requirements. A good solution was the Certal aluminum alloy 7022, which has a yield strength of $490$ MPa and a young modulus of $72$ GPa, giving a maximal elastic deformability of $0.068\%$. This is higher than the maximal strain for the strain gauge, which is $0.03\%$, so we will be able to use the strain gauge on its full scale.

### 3.1.7 Quality of the design

Before we start designing we also need to know how to judge what is the quality of a load cell. As we saw in subsection 2.4.3, load cells that have a diagonal system matrix are good because they do not require as much computation and have a good differentiation of the different force/moment elements, reducing the effect noise can have.

However, as we saw in the examples of subsection 2.4.5, load cells that have a diagonal system matrix have a complex 3D structure. This is not suitable for integration in the Roombots modules, so we will not try to have a diagonal matrix. But the same kind of idea can be kept for non diagonal load cells, meaning that it is good to have big difference of outputs for the different force/moment components, to insure that the system is not close to singularity.

Another important quality factor for load cells that are not 6-axis ones is that the unmeasured force/moment components must affect the other measurements as little as possible.

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\(^1\)The webpage for ordering those strain gauges is:

http://www.microninstruments.com/store/prod-Semiconductor-_U_-Gage_SS_037_022_500PU_S2-87.aspx
3.2 The path to the solution

In this section, we present the different load-cell models that have been investigated and their evolution in a chronological order.

3.2.1 Using SolidWorks

As explained in subsection 2.3.3, we needed a finite element analysis software to design the mechanical structure of the load-cell. For this purpose we used SolidWorks and its simulation toolkit, because the software was readily available at EPFL, and the SolidWorks model would be directly usable for production in the workshop.

Designing a load-cell in SolidWorks was not trivial. For each different model we wanted to investigate, the optimization process was of high dimensionality. Indeed, every time we changed some parameters such as the thickness, the width, the length or the position of some features, the impact of this change had to be analyzed for all the force/moment components and at all the strain gauges locations.

This was very time consuming because there was no automated data collection, so only some of the models were analyzed in detail. For the other models, a more global look at the graphics provided by SolidWorks was sufficient to either discard or modify them.

3.2.2 The first model

The first model we designed was composed of two different parts: a first structure that would replace the floor of the hemisphere (part 44 in figure 3.2) and that would measure the Mx, My, and Fz components, and a second structure that would replace the ball bearing holder (part 1 in figure 3.2) and that would measure the Mz component.

The first part (fig. 3.3) is composed of three beams holding two concentric rings together. The outer ring is attached to the shell of the module and the inner ring is attached to the ball bearing and gearbox. All the components of the load are transmitted through the beams, and this is where the strain is measured.

In this model we measure the bending strain, so the strain gauges are placed in at the bases of each beam. We want to use half-bridge circuits, so the strain gauges are placed in pairs, one on the top side and one on the bottom side of each beam.

Since this structure must measure Mx, My and Fz, the beams must be flexible in those directions. That is why they are thin. On the other side, we do not want the other force/moment components to have a big influence here so the beams are wide. Figure 3.4 shows the strain distribution resulting of a Mx moment.

The structure has three beams (instead of four, which would be more intuitive) in order to fit to the symmetry of the shell (cf. figure 3.5). Indeed, the
Figure 3.3: First part of model 1

Figure 3.4: Analysis of the first part of model 1 in SolidWorks. A moment Mx of 5 Nm is applied to the structure, and the color represents the resulting strain. The part on top of the load cell is only there to apply the torque and is not part of the model. We can see that the higher strain occurs at the base of the beam as predicted.
shell holds the ring in three places, and it is important to preserve the symmetry in a load cell. Picture 3.6 shows how the strain pattern becomes more complex if the symmetry is not preserved.

The second part (fig. 3.7) is an adaptation of the ball bearing holder, and we keep its general shape so that it fits with the other parts. It has three pairs of parallel beams, that transmit the $M_z$ moment from the gearbox to the floor of the hemisphere. Two strain gauges are placed in pair at the base of one beam to measure the bending strain.

With this model (including the two parts), we do not get a diagonal system matrix, but this does not really matter. As long as we get a non-singular matrix, we can compute its inverse to obtain the force/moment components out of the strain gauge signals.
Figure 3.7: Second part of model 1

Figure 3.8: Analysis of the second part of model 1 in SolidWorks. A moment Mz of 25 Nm is applied to the structure.
3.2.3 Model 2

Model 2 is an evolution of model 1. Cuts have been done in the ring structure to release the constraint at the end of the beams. This makes the beams behave more like free end beams (cf. subsection 2.3.3), which have a better strain distribution for measurements. This can be seen in figure 3.9.

The ball bearing holder part remains the same as in model 1.

![Analysis of the first part of model 2 in SolidWorks. A moment Mx of 5 Nm is applied to the structure. Comparison with figure 3.4 shows that the cuts have a good effect on the strain distribution in the beams.](image)

3.2.4 Model 3

With model 3 (fig. 3.10), we wanted to measure the forces Fx and Fy instead of the moments Mx and My. The three narrow beams would bend when a force is applied and strain gauges would measure the bending strain on the sides of those beams.
The problem with this model was that it would have been hard to place pairs of gauges experiencing antisymmetric strains. As we can see on figure 3.11, the positive strain (in red) is easy to measure, but the negative one (in blue) is either at the ends of the beam, or in the middle at the back, two places where it is not possible to glue gauges.

Another problem with this model was that the Mx and My moments would have a non-negligible effect on the measurements because they would twist the narrow beams.

3.2.5 Model 4

With model 4 (fig. 3.12), we switched from measuring the bending strain to measuring the shear strain. We did this for two reasons. First, the shear strain is measured on the side of the beam, so we do not need to place gauges on the bottom of the beams like in model 1 and 2. Second, the shear strain is affected the same way by the thickness and the width of the beam. This makes it easier to design a beam on which Mz can also be measured in addition to Mx, My, and Fz. So there is no need for a second part, which makes things simpler and lighter.

We also want to use half-bridge circuits on this model, so we place the strain gauges in pairs with an orientation of $+45^\circ$ and $-45^\circ$ on the side of each beam. A fourth pair is placed on the top of one of the beams to measure the Mz component (fig. 3.13).
Figure 3.11: Simulation of the bending beams of model 3

Figure 3.12: Model 4
3.2.6 Model 5

Model 5 (fig. 3.14) is an evolution of model 4 where niches have been cut in the side of the beams. This let us measure the shear strain closer to the center of the beam, where it has a higher value, without changing the width of the beam, which was already optimal.

On figure 3.15, we can see how the niche focuses the strain. Having a higher strain in the niches enables us to have a better resolution in our measurement without weakening the structure.
Figure 3.15: Comparison of the strain distribution with and without niches. The plot shows the strain in the axis of the strain gauges, which is parallel to the side of the beam, with an angle of 45° from the horizontal.

3.3 Final solution

Finally, we decided to test an adaptation of model 5 for real. There were certainly some aspects that could still be improved, but the time constraint forced us to stop there.

3.3.1 Realization

We made three changes from model 5 to the final model (fig. 3.16).

The first one was to make it thinner in the places that were not critical, in order to make it lighter, and to fit the shell and the ball bearing holder interface. A thicker ring was left to insure a good stiffness of the structure.

The second change was to make removable beams, in order to facilitate the gluing of the strain gauges in the niches, which we thought would be a delicate operation. As a result, the load-cell is composed of five parts: the outer ring, the inner ring and three beams. We decided that the beams would be glued to the rings for a good load transmission.

The third change was to add some floor surface between the inner and the outer rings in case some extra device needs to be placed there someday.

Those parts were ordered to the "Atelier de l’Institut de Production et Robotique” (ATPR)\(^2\) at EPFL, which did a very good job.

We also ordered a backup model (fig. 3.17), because we were not sure how hard it would be to glue the strain gauges in the niches, and if it was a good idea to have a load cell in several parts. This model (model 7) is an adaptation of model 4.

\(^2\)webpage: http://sti-ateliers.epfl.ch/site/sti-ateliers/atpr
Figure 3.16: Final model

Figure 3.17: Backup model
Alexander Sproewitz took care of the gluing and curing of the strain gauges on the load-cells. This was a time consuming and tedious task, because the curing procedure is long, and the strain gauges are very small. Figure 3.18 shows the beam with two strain gauges glued on it.

![Image of a beam with strain gauges](image)

Figure 3.18: Top and side views of the beam that has the top strain gauge pair in addition to the side one. The gauges are a bit less than one millimeter long. Connecting pads have been attached to the small wires of the strain gauges to connect them to the Wheatstone bridges.

### 3.3.2 Simulation data

We ran finite element analyses on SolidWorks to get the expected strain that would experience each of the strain gauges pairs for each force/moment components. Those results are show in table 3.1. P1, P2 and P3 are the strain gauge pairs placed on the side of the beams, starting with the beam in the X axis and turning clockwise. P4 is the pair placed on the top of the beam in the X axis. The values in the table are the difference of strain between the two gauges of each pair, in percentage of elongation per Newton (for the force components) or per Newton Meter (for the moment components).

<table>
<thead>
<tr>
<th></th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>6.36E-5</td>
<td>1.08E-6</td>
<td>-2.01E-6</td>
<td>-1.56E-6</td>
</tr>
<tr>
<td>P2</td>
<td>-3.31E-5</td>
<td>5.76E-5</td>
<td>-1.16E-6</td>
<td>-1.63E-6</td>
</tr>
<tr>
<td>P3</td>
<td>-3.44E-5</td>
<td>-6.01E-5</td>
<td>-1.28E-6</td>
<td>-1.70E-6</td>
</tr>
<tr>
<td>P4</td>
<td>-9.40E-8</td>
<td>1.17E-4</td>
<td>-3.29E-5</td>
<td>1.15E-8</td>
</tr>
</tbody>
</table>

Table 3.1: Simulation results of the differential strain for each strain gauge pair for each force/moment components. Values are in elongation % per Newton or Newton meter.

We can then compute the corresponding voltage signals at the output of the bridges using equation 2.3 assuming we power the bridges with 5V and that the gauge factor is 150. The expected voltage signals are shown in table 3.2.

We can see that the output signals will be very different for each force/moment components and that the system is far from singularity.
Table 3.2: Simulation results of the voltage signal at the output of each Wheatstone bridge for each force/moment component. Values are in Volts per Newton or Newton meter.

<table>
<thead>
<tr>
<th></th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>2.39E-2</td>
<td>4.05E-4</td>
<td>-7.54E-4</td>
<td>-5.83E-4</td>
</tr>
<tr>
<td>P2</td>
<td>-1.24E-2</td>
<td>2.16E-2</td>
<td>-4.34E-4</td>
<td>-6.10E-4</td>
</tr>
<tr>
<td>P3</td>
<td>-1.29E-2</td>
<td>-2.25E-2</td>
<td>-4.81E-4</td>
<td>-6.36E-4</td>
</tr>
<tr>
<td>P4</td>
<td>-3.53E-5</td>
<td>4.37E-2</td>
<td>-1.23E-2</td>
<td>4.30E-6</td>
</tr>
</tbody>
</table>

So we can compute the load cell system matrix by inverting 3.2, as we saw in subsection 2.4.2.

\[
L = 1000 \times \begin{pmatrix}
0.0280 & 0 & 0.0028 & -0.5707 \\
0.0227 & 0.0207 & 3.9783 & -4.2 \\
-0.0475 & -0.0198 & -3.8187 & 2.9796 \\
-0.0007 & 0 & 0.0725 & 0.0667 \\
\end{pmatrix}
\]

The Fx and Fy components cannot be included as input to this 4-axis load cell and must therefore be considered as perturbations. We also measured their effect in simulation for P1 and P4 (P2 and P3 experience similar perturbations as P1) and computed the resulting perturbation they should have on the voltage signals. This is shown in table 3.3.

<table>
<thead>
<tr>
<th></th>
<th>Fx</th>
<th>Fy</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>4.00E-6</td>
<td>-4.96E-6</td>
</tr>
<tr>
<td>P4</td>
<td>-6.15E-7</td>
<td>-1.63E-4</td>
</tr>
</tbody>
</table>

Table 3.3: Simulations results of the voltage perturbations due to Fx and Fy on the signals of P1 and P4. Values are in Volts per Newton.

We can see that for P1, the perturbations from Fx and Fy are much smaller than the contributions from the other components, so there is no problem there. However, for P4, the perturbation from Fy is large and could have an influence on the measurements.

This was a problem we had in several previous models, and we did not achieve to correct it completely. From model 4 to model 5, the niches improved the situation by reducing the Fy perturbation by 6, but we did not have time to work on it further.

### 3.4 Electronics

#### 3.4.1 Initial plan

The electronics for the acquisition of the signals is an important part of a load cell. The Wheatstone bridge is usually the first stage of the circuit, but the
small voltage signal that comes out of it must then be handled with care to be readable by a micro-controller without too much noise.

The initial plan was to add several stages to the circuit after the Wheatstone bridge. First the signal would be filtered by passive elements (such as a RC filter), and then it would be amplified. Having an amplifier for each Wheatstone bridge would allow the signal to be amplified before traveling a long distance, which can add noise. It would also allow the amplification of each pair to be tuned individually. Then the signals from all the pairs would be gathered into a multiplexer, which would connect to the micro-controller. Figure 3.19 shows a sketch of this circuit.

A power and signal bus would have been done on a PCB to connect everything nicely.

### 3.4.2 Backup solution

Unfortunately, we were very short on time, and the PCB workshop at EPFL was not fully operational, so we did not get the PCBs in time.

So we decided to solder Wheatstone bridges out of simple resistors (fig. 3.20) to see if we could still measure something.

We noticed something strange while assembling the Wheatstone bridges: the resistance across the glued strain gauges was ranging from 320 to 360 Ω instead of the expected 540 Ω, and some of the pairs which resistance was suppose to match had more than 15 Ω of difference. We do not know if this decrease of resistance comes from. Maybe it is due to residual stress from the glue or to the effect of the heating.

This was a problem of three reasons. First, if the Wheatstone bridge is
unbalanced, it creates an output offset. But this problem can be correcting by removing the offset, which was already planned. Second, if the strain gauges do not have the same resistance, the gain of the Wheatstone bridge is modified. And third, since the semiconductor strain gauges are not exactly linear, a residual stress can bring them into a region where their gauge factor is different. This can modify the Wheatstone bridge gain too.

Little could be done to correct this. We just changed the 540 Ω resistors we first wanted to use for some 330 Ω ones.

Figure 3.20: Realization of a Wheatstone bridge out of simple resistors and wires. This one was a first test on the backup model.
Chapter 4

Results

4.1 Data collection

4.1.1 Experiment setup

We developed an experiment setup to test the load cell (fig. 4.1). The setup is composed of a plate where the load cell can be fixed by screws in a similar way that it would be fixed to the shell of the hemisphere, and of a lever that can be attached at the center of the load cell the same way as the ball bearing would be attached to it. We wanted to test the load cell in conditions similar to what it would experience once in the Roombot module.

The plate can then be clamped to a table and the lever can be pulled in several directions with a dynamometer to simulate different kind of loads. Unfortunately we had very little time left and very few machining facilities left so we were not able to build a lever that could apply a measure Mz moment.

The input of the Wheatstone bridge of each strain gauge pair was powered at 5V by a power supply.

4.1.2 LabVIEW

Since we did not have the complete electronic circuit available to integrate a microcontroller to the load cell, we use a National Instrument USB 8006 acquisition device to read the signals from the Wheatstone bridges. This device was connected to a PC running Windows and we used LabVIEW to collect the data.

We built a VI (virtual instrument) that can calibrate the signal by removing their offset when the load cell is at rest, and then display (fig. 4.2) and collect the data of the four strain gauge pairs.
Figure 4.1: Experiment setup.

Figure 4.2: Interface of the VI for the acquisition of the data on LabVIEW. Those plots are the result of a full rotation of the direction of the force applied on the lever.
4.2 Data analysis

We did some experiments with the setup for Mx, My and Fz in the positive and negative directions for values from 0.5 Nm to 2.5 Nm for Mx and My and from 5 to 25 N for Fz. The results were approximately linear, and we computed the gains for each pair. The results are shown in Table 4.2.

<table>
<thead>
<tr>
<th></th>
<th>Mx</th>
<th>My</th>
<th>Mz</th>
<th>Fz</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1E-2</td>
<td>6E-3</td>
<td>-</td>
<td>-1.5E-3</td>
</tr>
<tr>
<td>P2</td>
<td>-3.5E-3</td>
<td>-1.1E-2</td>
<td>-</td>
<td>-3.5E-3</td>
</tr>
<tr>
<td>P3</td>
<td>-3.5E-3</td>
<td>9E-3</td>
<td>-</td>
<td>-1.5E-3</td>
</tr>
<tr>
<td>P4</td>
<td>-1E-4</td>
<td>4E-3</td>
<td>-</td>
<td>1.2E-4</td>
</tr>
</tbody>
</table>

Table 4.1: Gains computed from the experiment data. Values are in Volts per Newton or NewtonMeter.

Comparison with Table 3.2 shows that the experimental results are not really close to what simulation had predicted. However, the order of the values (i.e., which is bigger than which) inside columns or rows and the signs are generally respected.

A combination of several reasons could explain the difference of the results between the simulation and the experiment. A first reason could be that SolidWorks simulation is perhaps not precise enough to take some effects into account. A second reason could be that the interface between the glued beams and the rings of the load cell cannot be modeled as we did it in SolidWorks. A third reason, which is very likely, could be that the strain gauges do not have the expected behavior. We already saw that their resistance was strange, so maybe their gauge factor has been affected too. And a fourth reason could be that the gauges are not well enough aligned in the desired position. This would prevent them from seeing pure shear strain.

However, this does not mean that the load cell is unusable. It can still be fully characterized and its system matrix can be computed.
Chapter 5

Conclusion

The objective of this semester project was to design and integrate a multi-axis force/moment sensor in the Roombot modules to facilitate their control in different tasks.

After an extensive literature research on the subject, different models have been investigated in simulation and have led us to a solution we implemented for real. The experiments we did on this sensor gave us results that were not close to what was predicted by the simulation. The reasons for those differences should be investigated, and perhaps a solution could be found to reduce them.

Maybe the reason could be found in the stain gauge bonding procedure. Indeed, we were a little bit optimistic concerning how hard it is to glue such small gauges in niches properly, with the correct $45^\circ$ angle. We understand why this operation is usually done by the strain gauge manufacturers themselves.

Despite the fact that the results are different from expected, the properties of the sensor can still be characterized and the sensor could still be used in a Roombot. But each sensor should be tested separately to determine its system matrix, which should be stored in the Roombot module’s memory.

No time was left to finish the electronic implementation of the sensor, and this is left as future work. This includes the interfacing with the electronics and microcontroller of the Roombot modules too.

And what will be done with the data provided by this sensor? This is a topic for future work that promises to be interesting and vast.

5.1 Acknowledgment

I would like to thank my supervisors Alexander Sproewitz and Rico Moeckel for their support, their availability and their investment in this project.

I also would like to thank Professor Auke Jan Ijspeert for welcoming me in his laboratory and giving me the opportunity to work on this project in a dynamic environment.
Bibliography


