Seamless integration of force sensing and position monitoring on robot arms with Dragonfly® strain sensors

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Abstract
Worms Dragonfly® sensors are strain sensors with a sensitivity which outperform standard strain gauges. Deformations down to 10ndef can be measured accurately. In this paper several enhancements to a commercial robot using Dragonfly® sensors are suggested. By gluing sensors on the robot structural parts and on its head, the touching force is estimated, as well as the oscillations of the head around its target position due to the robot compliance. Contrary to integrating traditional force cells, embedding Dragonfly® sensors in a structure does not change its mechanical behavior, nor does it require to adapt the structure's design.

Keywords
Piezoelectric sensor, force cell, strain measurements, robot monitoring

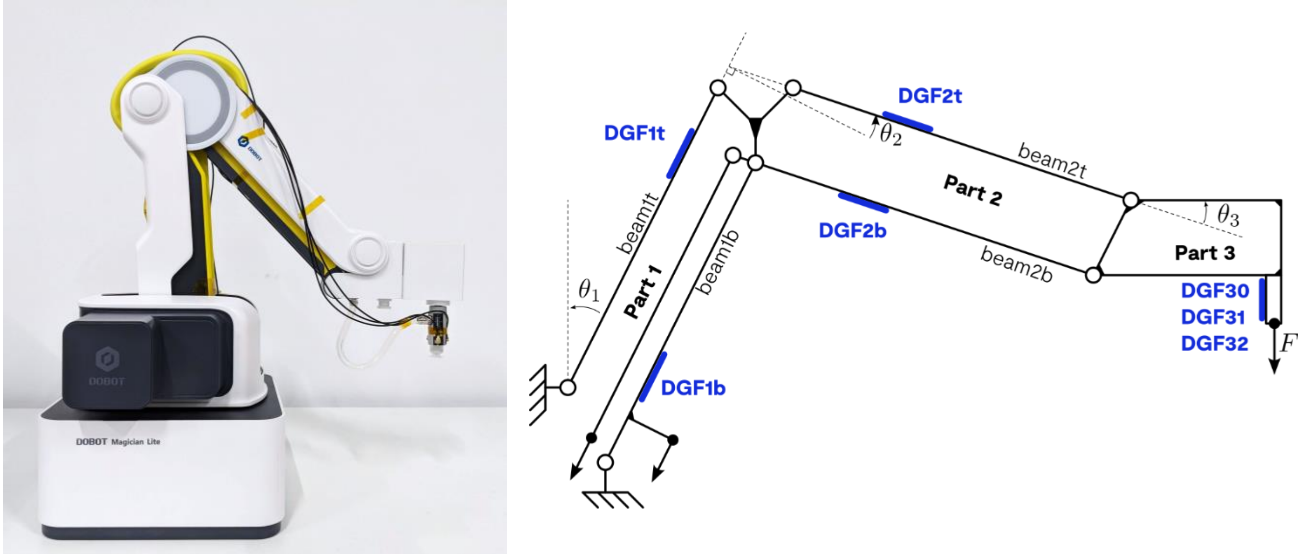

Figure 1 : picture of the studied arm robot, and schematics of its kinematics with the location of the added Dragonfly® sensors.

1 Introduction

Robots and industrial machines are widely used to perform repetitive tasks. They are programmed to perform well as long as the external conditions do not vary (the objects they take are always at the same position and have identical shapes, the temperature is constant), nor do internal parameters (stiffness of mechanical parts, wear in the joints, etc).

To adapt to these changes or stop before permanent damages to the machine occur, sensors are needed to monitor the machine and its environment. Typically, force information may be of particular interest, to limit the machine displacement before breaking the parts it interacts with or the machine itself.

Inserting a force cell in a machine creates strong design constraints as the force cell must be in series with the structural parts, which creates weaknesses in the structure. Another approach to monitor the force passing through structural parts is to glue strain gauges to estimate the mechanical constraints at critical locations. However, industrial machines and robots are usually made of very rigid metal parts which deform very little to meet position accuracy requirements. Conventional resistive strain gauges have a high background noise which makes it impossible to measure deformations smaller than 10µdef. Thus, it is often impossible to accurately estimate the deformation of the structural parts of a machine during its operation.

Dragonfly® piezo strain sensors (DGF), developed by Wormsensing have a sensitivity which is around 1000 times higher than resistive strain gauges. Deformations down to 10ndef can be accurately measured. They are therefore a candidate of choice to monitor the deformation of rigid structural parts of industrial machines and robots, to derive the force passing through them or to estimate relative displacements.

In the present study, we focus on a commercial robot with no sensing abilities and show how it can be enhanced by adding Dragonfly® sensors to measure the force applied by the robot on objects and estimate the unwanted displacement of the robot head due the compliance of its structural parts.

2 Touch force estimation

The first goal of this study is to estimate the force applied by the robot head on the objects it interacts with, shown as F in Figure 1. This force is of major interest, as it will help to correctly seize objects without damaging them or the robot itself. To estimate this force, we suggest two methods depending on the available space and complexity of the robot head:

1- The force in the Z-direction is estimated with the Dragonfly® sensor DGF2t, which is located on the top beam of part 2. This method is particularly interesting if no force or Dragonfly® strain sensors can be integrated in the robot head (part3) due to application constraints (not enough space, environmental conditions, etc.).

2- The force is estimated with the Dragonfly® sensors DGF30, DGF31 and DGF32 (see Figure 5), located on the suction cup holder. This time the three components (in X Y and Z directions) of the force are estimated. If it is possible to locate a Dragonfly® sensor close to the tip of the robot arm, the force will most likely be estimated with higher accuracy.

2.1 Experimental setup

The Dobot Magician Lite robot is equipped with seven Dragonfly® sensors, positioned at the locations described in Figure 1 and Figure 9. The angle θ_1 is fixed at 0°, and θ_3 is varied between 0 and 80°. The piezoelectric force cell is positioned below the robot head, such that the robot applies a static force around 5N on the force cell. A picture of the setup is shown in .

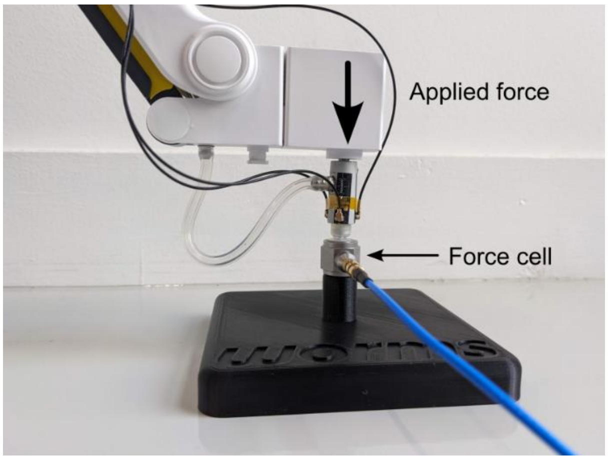

Figure 2 : experimental setup for measuring the relation between DGF2t and the force cell (PCB Piezotronics 208C02).

The robot is then configured to perform vertical oscillations of 1mm amplitude in the Z-direction, with increasing frequency over time. This results in an oscillating force on the force cell, which is recorded together with the Dragonfly® sensor signals. The time recordings of DGF2t and force cell are shown in Figure 3.

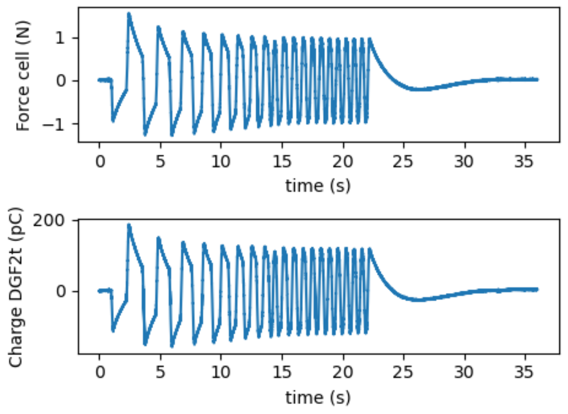

Figure 3 : time recordings of DGF2t and force cell during a force calibration experiment.

The force cell and the Dragonfly® sensor are both piezoelectric devices and are not designed to measure infinitely slow variations. The calibration factor between the Force and the DGF signal is obtained by computing the transfer function between the two signals, and averaging between 1 and 8 Hz, where the transfer function amplitude is flat (see Figure 4). Above 8Hz the first modes of the robot come into play and the DGF2t and force cell signals are no longer proportional.

As a result, for each angle θ_3 we measured the proportionality constant between the force applied on the robot head and the signal of DGF2t. The next step is to show that the vertical force on the head can be estimated using the DGF2t signal, knowing the angle θ_3.

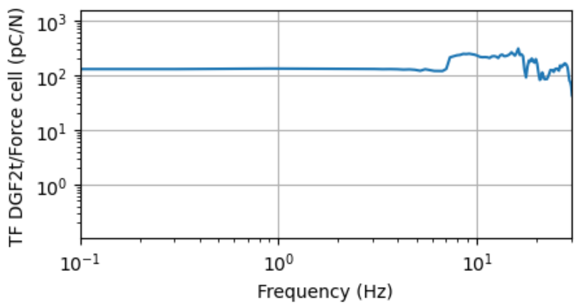

Figure 4 : transfer function between the DGF2t and the force cell when the robot oscillates in the vertical direction while touching the force cell.

2.2 Force estimation using DGF2t

The goal of this section is to estimate the Z-component of the force F applied at the suction cup, using the signal from the DGF2t.

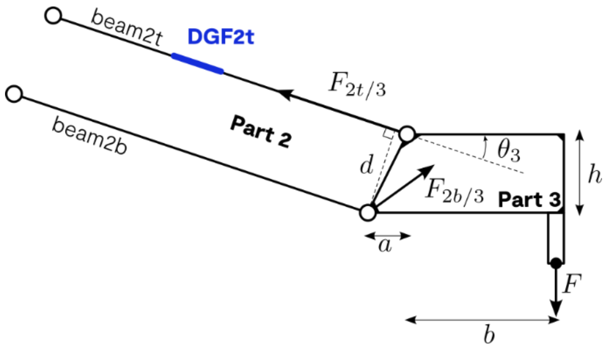

Figure 5 : Schematics of the robot head (parts 2 and 3).

The Dragonfly® sensor DGF2t is glued on the top beam of part 2 (beam2t). As beam2t is only connected to two revolute joints, the applied forces by the two joints are colinear with the beam itself. The beam2t is thus in a pure traction/compression state, with no bending moment. As a result, the sensor DGF2t which measures the local deformation of the beam will output a charge proportional to the force in the beam written $F_{2t/3}$ on Figure 5. The charge measured by DGF2t is written q_2 and reads:

$$q_2 = \alpha_2 F_{2t/3}$$

where α_2 (pC/N) is the sensitivity of the DGF2t to the force in beam2t, which depends on the sensitivity of the Dragonfly® sensor (in pC/µdef), and on the properties of beam2t (how it deforms at the sensor location when submitted to an axial force).

The force balance on part 3, yields the relation between the applied force F and $F_{2t/3}$:

$$F_{2t/3}(\theta_3) = \frac{a+b}{d(\theta_3)} F(\theta_3)$$

where a, b and d are defined in Figure 5. The relation between d, θ_3 and the geometrical parameters a and h is obtained analytically:

$$d(\theta_3) = \sqrt{(x-a)^2 + y^2}$$

where:

$$x = \frac{1}{tan(\theta_3) + 1/\,tan(\theta_3)} \left(\frac{1}{tan(\theta_3)} a - h \right)$$

$$y = \frac{1}{tan(\theta_3) + 1/\,tan(\theta_3)} \left(\frac{1}{tan(\theta_3)} h + a \right)$$

As a result, the charge measured by DGF2t reads:

$$q_2(\theta_3) = \alpha_2 F_{2t/3}(\theta_3) = \alpha_2 \frac{a+b}{d(\theta_3)} F(\theta_3)$$

The parameter α_2 is estimated using the first measurement, at the angle $\theta_3 = 0°$:

$$\alpha_2 = q_2(\theta_3 = 0°) / \left(\frac{a+b}{d(\theta_3 = 0°)} F(\theta_3 = 0°) \right)$$

For the other angles, the transfer function between q_2 and F is compared to the analytical relations, as in theory:

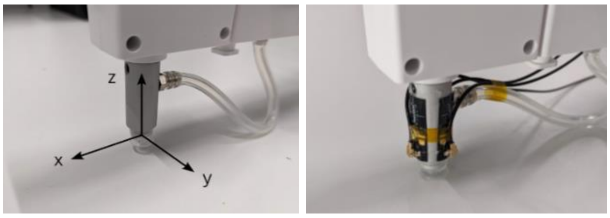

Figure 8 : picture of the suction cup on the head of the robot, before and after installing the Dragonfly® sensors DGF30, DGF31 and DGF32.

$$\frac{q_2(\theta_3)}{F(\theta_3)} = \alpha_2 \frac{a+b}{d(\theta_3)}$$

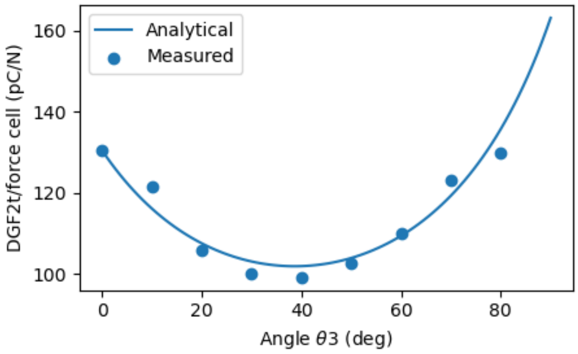

Figure 6 : Measured and estimated relation between the charge generated by DGF2t and the vertical force on the robot arm.

Figure 6 shows that the measured force applied on the robot head can be accurately estimated using the signal from the DGF2t sensor, for all angles between 0° and 80°.

As an example, the measured force during the experiment at $\theta_3 = 70°$ is plotted in Figure 7. This figure shows a very good agreement between the measured and estimated forces, which demonstrates the ability of the sensor located on the top of beam2t to estimate the touching force of the robot on an object.

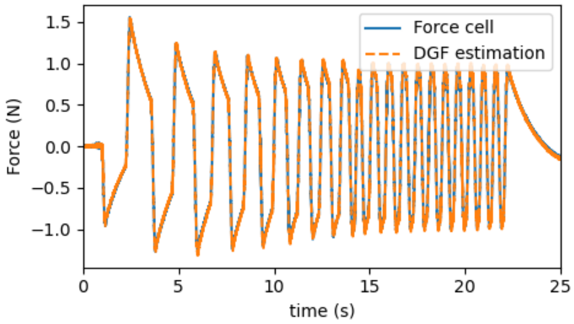

Figure 7 : measured and estimated force during the experiment at 70°.

2.3 Force estimation with Dragonfly® sensors located on the robot head

In this section, three Dragonfly® sensors are glued on the metal piece of the robot head holding the suction cup. Without changing the design of the robot head, we will show that adding Dragonfly® sensors turns the robot head into a 3-directional force cell.

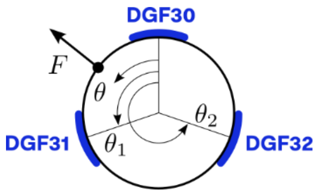

Figure 9 : Angular positions of the Dragonfly® sensors on the suction cup holder (top view).

When a force F is applied on the suction cup, it will deform the metal part, in different ways depending on the direction of the force:

- A vertical force (Fz) will evenly compress the cylinder, so all sensors will measure the same value.
- A horizontal force (Fxy) in the (XY)-plane will bend the cylinder, resulting in different signals on the three sensors.

Numerical simulations of a force applied at the end of a cylinder show that the charge generated by the three sensors read:

$$q_0 = F_{xy}\alpha_{xy}\cos(\theta) + \alpha_z F_z$$

$$q_1 = F_{xy}\alpha_{xy}\cos(\theta - \theta_1) + \alpha_z F_z$$

$$q_2 = F_{xy}\alpha_{xy}\cos(\theta - \theta_2) + \alpha_z F_z$$

We chose $\theta_2 = -\theta_1$, so the Fxy and Fz force can be retrieved from the sensor signals as follows:

$$F_{dgf\_x} = \frac{1}{3\alpha_{xy}} \mathrm{Re}\left(q_0 + e^{i\theta_1} q_1 + e^{-i\theta_1} q_2\right)$$

$$F_{dgf\_y} = \frac{1}{3\alpha_{xy}} \mathrm{Im}\left(q_0 + e^{i\theta_1} q_1 + e^{-i\theta_1} q_2\right)$$

$$F_{dgf\_z} = \frac{1}{3\alpha_z} (q_0 + q_1 + q_2)$$

The parameters α_{xy} and α_z are calibrated experimentally by a similar procedure as in section 2.1. The force cell is placed either vertically to sense the force in the Z-direction or horizontally to sense the force in the (XY) plane. The head is rotated around Z to apply the force in various directions in the (XY) plane.

To validate the method, the robot is moved in the X-direction until it hits the force-cell, then back until there is no more contact, then the head is rotated by 90° around Z, and the robot is moved along X until it hits the force cell a second time, see Figure 10.

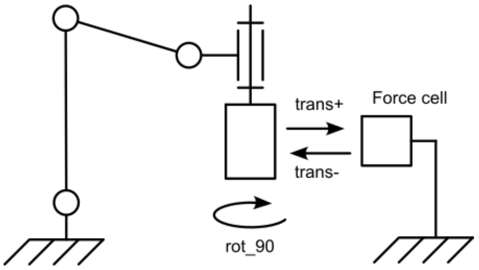

Figure 10 : sequence of movements to validate the force estimation using Dragonfly® sensors.

The time signals of the force cell and of the force estimated using the Dragonfly® sensors and equations above is plotted in the figures below, when the robot performs the sequence of movements [trans+, trans-, rot_90, trans+, trans-].

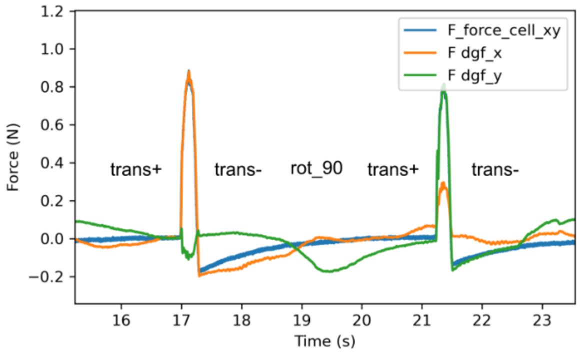

Figure 11 : Comparison between the force measured by the force cell and the force estimated using the DGF sensors, for impacts in the X and Y directions.

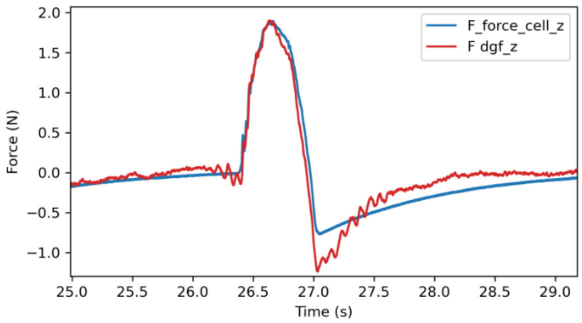

Figure 12 : Comparison between the force measured by the force cell and the force estimated using the DGF sensors, for an impact in the Z-direction.

Figure 11 and Figure 12 show that the force during the impact is very well estimated in the three directions using the three Dragonfly® sensors placed on the cylindrical suction cup holder. Between the impacts, especially the impacts in the X and Y directions in Figure 11, the estimated force differs from the steady discharge of the piezo-electric force cell. This may be due to the rotation of the head, on which the vacuum tube is fixed and may apply a small force on the suction cup holder when the head is rotated.

In terms of sensitivity, the custom force cell made of Dragonfly® sensors reaches a similar performance as the commercial force cell that we used in this experiment. When no force is applied, the force noise floors are:

- Force cell (PCB Piezotronics 208C02): 0.0033 Nrms
- DGF estimation: 0.0022 Nrms

Of course, these values depend heavily on the configuration in which the Dragonfly® sensors are installed, especially on the stiffness of the part where the sensors are glued.

2.4 Conclusion on force estimation

We have demonstrated that adding Dragonfly® strain sensors to an existing robot without modifying its geometry, enables measurements of the force applied by the head on objects it carries. Two options have been suggested: either by instrumenting only the robot arm, in cases where instrumenting the head is not possible due to practical constraints, or by gluing the sensors directly on the head for an accurate estimation of the force in the three directions. Further investigations could be carried out to also estimate the moments applied by the head on the carried objects.

3 Head displacement estimation

The second goal of the present study is to estimate the relative position of the robot head compared to its theoretical position (if the robot were perfectly rigid), in the Z-direction. As a matter of fact, one of the critical performance metrics of robot arms is their position accuracy, which will define the tasks they can be used for. Typically, robots used in the industry need to reach a positioning accuracy lower than 50μm. Moreover, when the robot stops at its target position, it will oscillate during a given time because of the compliance of its joints and structural parts. Here we will try to estimate the oscillations of the position of the robot head around its target using the Dragonfly® sensors shown in Figure 13.

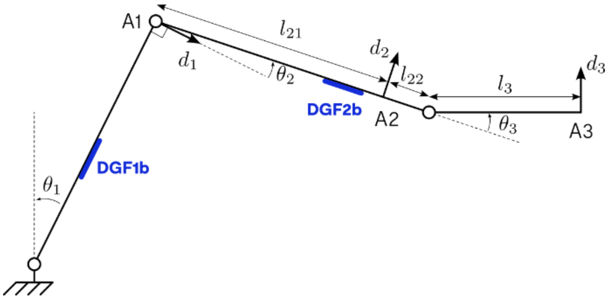

Figure 13 : simplified kinematics of the robot, and definition of the estimated displacements d_1, d_2 and d_3.

3.1 Methodology

The global idea is that the deformation measured by the Dragonfly® sensors is proportional to the deflection of the different parts of the robot (and to the joint flexibility). The following assumptions are made, to simplify the problem:

- The relative displacement d2 of the point A2 with respect to part 1 is assumed to be normal to the part 2, and proportional to the signal of DGF2b:
$$d_{2/1} = q_2/\alpha$$
- Due to the kinematics of the robot (see Figure 1), θ_1 variations create almost no displacement of the head in the Y direction.
- The head stays always horizontal, so:
$$\theta_1 + \theta_2 + \theta_3 = 0$$

The coefficient α defined above describes the proportionality relation between the charge generated by the Dragonfly® sensor and the relative displacement between part 1 and part 2. It is estimated by placing an accelerometer at the position Acc2 (see Figure 14) and computing the transfer function between the acceleration signal and the DGF signals.

Once the parameter α has been identified, the robot will be operated in an arbitrary movement, and the acceleration of the head measured by the accelerometer at position Acc3 (see Figure 14) will be compared to the estimated acceleration using the Dragonfly® signal.

3.2 Calibration of the α parameter

The first step is to find the parameter α which links the deflection of the second joint to the signal of DGF2b. The accelerometer is placed at the position Acc2 (see Figure 14). The robot is excited with an electrodynamic shaker, playing a 20s-long exponential sweep between 0.1Hz and 30Hz.

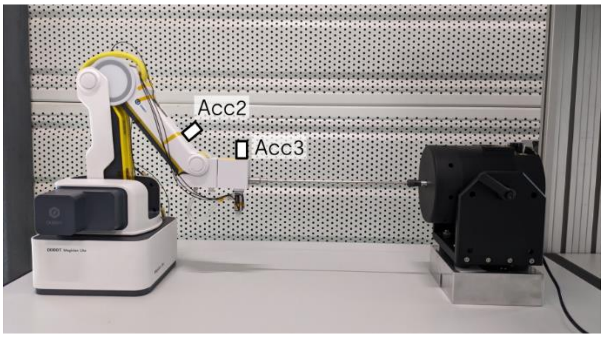

Figure 14 : excitation of the robot arm using an electrodynamic shaker to calibrate the relation between the joint displacement and the Dragonfly® signals.

The transfer function between the DGF signal and the accelerometer is plotted for three values of the angle θ_2 in Figure 15. The transfer function has been multiplied by $(2\pi f)^2$ to convert the acceleration into displacement.

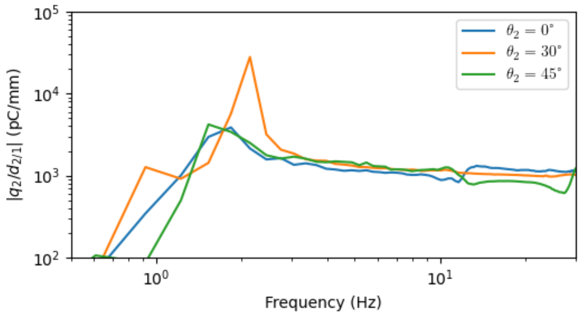

Figure 15 : transfer function between the DGF sensor DGF2b and the accelerometer located at position Acc2 multiplied by $(2\pi f)^2$ to convert the acceleration to displacement.

Figure 9 shows that the transfer function is flat between approximately 3 and 10Hz, meaning that

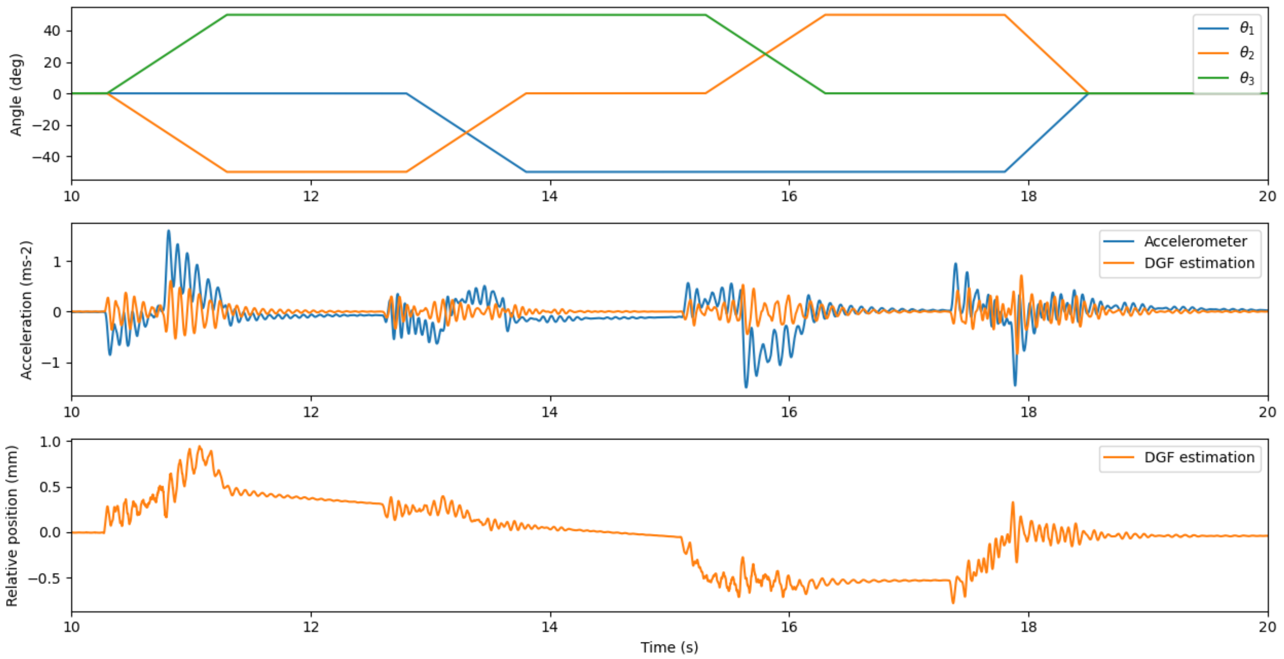

Figure 17 : acceleration when the robot joint angles are moved, measured at position Acc3 with the accelerometer and estimated using the DGF2b signal.

the Dragonfly® signal is proportional to the displacement. Below 3Hz, the cutting frequency of the accelerometer prevents us from acquiring meaningful data. Above 8Hz the first eigenmodes of the robot start affecting the results. Also, the amplitude of the transfer function does not seem to depend on the angle θ_2 which is a prerequisite for our method to work.

The coefficient α is estimated by averaging the transfer function between 2 and 8Hz. The obtained value is:

$$\alpha = 1200\text{pC/mm}$$

The final step is to derive d_3. Writing the kinematic relations yields:

$$d_3 = \frac{\alpha q_2}{l_{21}}(l_{21} + l_{23})\,cos(\theta_3)$$

The acceleration at position A3 is obtained by deriving the obtained d_3 two times with respect to time.

3.3 Experimental results

The robot is programmed to move in a circular manner: increasing θ_2, then θ_1, and then decreasing θ_2, then θ_1 back to their initial values. The robot motion is described in Figure 16.

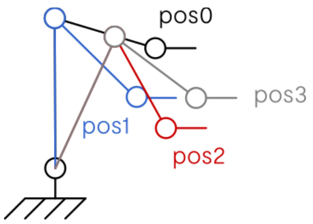

Figure 16 : movement of the robot during the sequence of joint rotations: increasing θ_2 (pos0 → pos1), then θ_1 (pos1 → pos2), and then decreasing θ_2 (pos2 → pos3), then θ_1 back to their initial values (pos3 → pos0).

The target angles as a function of time, the measured acceleration, and the acceleration at position Acc3 estimated by the method described in the previous section using the DGF2b sensor, are plotted in Figure 17.

Figure 17 shows that the acceleration estimated using the DGF2b sensor is very similar to the acceleration measured by the accelerometer, especially for the oscillations at a frequency around 10Hz which corresponds to the first eigenmode of the robot. The accelerometer captures the low frequency component due to the global movement of the robot head (negative if the head moves down, positive if the head moves up). As the Dragonfly® sensors only measure the deflections of the robot beams, they are not sensitive to rotations of the joints due to motor operation, which is why they do not capture the acceleration due to the robot joint rotations. However, as the angular position as a function of time should be known, the global acceleration of the head could be derived analytically and added to the oscillation part estimated by the Dragonfly® signals.

As the strain measured by the Dragonfly® sensors is proportional to the displacement, not only the acceleration can be estimated but also the relative position of the head compared to the target position, which is plotted in Figure 17. This shows that the head oscillates by around 0.5mm when the movement is finished. Thus, adding Dragonfly® sensors to the robot allows to track the exact position of the head, which may provide a very useful information for performing precise tasks with the robot.

A second test is performed, where the robot is fixed at a given angular position (θ_1=0°,θ_2=40°), and the head is hit by the hand to make it oscillate in the z direction. The measured and computed accelerations at position Acc3 are plotted in Figure 18. Again, a very good fit is obtained, this time without the low frequency offset of the measured acceleration due to the robot displacement. Figure 18 shows that the oscillations of the robot head can be accurately estimated when it hits or takes an object.

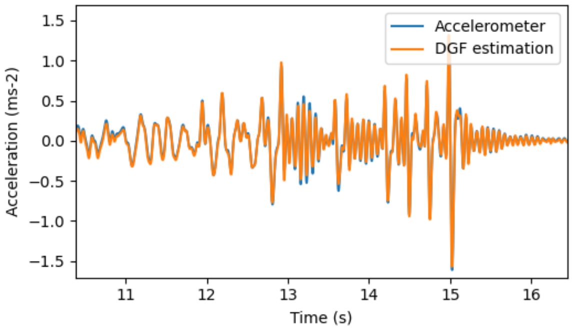

Figure 18 : acceleration of the robot head in the Z-direction when fixed at the position (θ_1=0°,θ_2=40°) and hit by the hand in the Z-direction, measured by the accelerometer and estimated using the DGF2b sensor.

Conclusions

In this study we have enhanced a commercial arm robot with Dragonfly® piezo strain sensors. The very high sensitivity enables to accurately monitor the deformation of the structural parts of the robot, and after a calibration stage this information can be processed to obtain useful information, such as the force applied by the robot on test objects, or the displacement of the robot head due to its compliance.

This is a breakthrough for robot use and optimization thanks to two main benefits:

- It becomes easier to integrate key functionalities such as force sensing and displacement monitoring in the design of new robots.
- Existing robots can be improved by adding force sensing capabilities without modifying their structure. The precision and versatility of present robots may be increased to reach complex practical use cases.

The principles which have been developed here can of course be extended to more complex structures and environments. This type of monitoring is possible even on very rigid parts which deform very little, thanks to Dragonfly®'s high sensitivity. It now becomes possible to measure the force in structural parts without redesigning them to meet the low sensitivity requirements of traditional strain gauges.