Integrating Temperature Sensing to a Reem-C's Fingers

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Abstract

The Reem-C is a robot manufactured by Pal Robotics that doesn't possess any sensory ability at the level of the fingers, at least in the version owned by ICS. This report presents a system that could provide the robot with temperature sensing by adding low-latency thermistors to a glove that integrates well with the robot's hand geometry and functionalities. This system consists of an Arduino reading the temperature off a voltage divider and transmitting the data over the User Datagram Protocol (UDP) to a Robot Operating System (ROS) master. The temporal response of the thermistors was measured and the analysis has shown that it is possible to trigger within ROS and within less than 0.5 seconds of proximity to an object that has reached 80 degrees Celsius a signal leading to a reflex behavior.

1 Introduction

Adding sensing ability to hand prosthetics is an active area of research, and a lot remains to be done. This line of work emerged from the observation that state-of-the-art robotic prostheses reach important limitations in approximating the finesse of the human motor system because they lack the complex sensory system and the sensory feedback that humans possess. This is the case with current humanoid hands, which for the most part lack temperature sensing. Detecting and sensing hot objects is not just a matter of safety but also provides a sense of embodiment, as shown in [9]. While ICS is well known for its implementation of a humanoid skin that integrate temperature sensing (see for instance [7]), the modular sensors used in a tiling fashion to emulate the human skin are too big to be added to the fingers and much less to the fingertips. This project designed a solution to this problem by mounting temperature sensors on a glove that fits the Reem-C's robotic hands.

In this context, the critical criteria defined for the selection of a temperature sensor were size and latency. To integrate well on a fingertip and not risk being damaged, temperature sensors can't spread over more than a few millimeters of area and can't be much thicker. This means that data processing should not occur on site and that the signal should ideally be transmitted by cables running along the robots' limbs to a processing unit. Besides supporting prehension and providing sensory feedback to the motor commands sent to the muscles, temperature sensing is above all a safety system. Without fast detection of temperature rises, humans would be in danger. Thus a latency of the order of a second turned out to be an important criterion the sensor and the entire system should meet. Other criterion such as the range (up to 150-200 degrees Celsius) were relevant and verified during the search for a sensor, but they didn't pose a risk to the project and could easily be met. Finally, it is worth noting that besides size and latency, the scope of this project limits the kinds of technologies that can be used.

2 Methods

2.1 Choice of sensors

The search for a temperature sensor assessed different options and required approximately two weeks time in the project. While technologies based on infrared light could be ideal solutions due to their low latency, they don't lend themselves to an easy integration on a glove. Besides they are rather bulky when compared with thermistors for instance. Hence the search quickly focused on the market of small, low-latency thermistors. Most of those available listed in their specifications a response time "in liquids" of the order of a few seconds, which we might expect to be greater in still air. Many times the manufacturers used other language to specify the latency and didn't describe their metrics. Very few thermistors had the potential to meet the required latency, and when they did (see for example [4], with a thermal time constant of 0.8 seconds in still air), the minimum order was 200 pieces while I barely needed 10.

The only available thermistor that could be obtained within the time constraints of this project came from the manufacturer TE connectivity (table 1). Their best model, the Series C, had unfortunately a lead time of 6 weeks. Therefore the slightly slower series B was selected. (see the complete product datasheet [3]).

Model	Dimensions (mm)	Response Time (sec.)	Range (Celsius)
Series A	4 x 2.5 x 0.3	0.9-1.1	-50 to 250
Series B	3 x 1.5 x 0.2	0.3-0.4	-50 to 250
Series C	2 x 0.9 x 0.15	0.18-0.2	-50 to 250

Table 1: Main characteristics of the thermistors produced by TE connectivity.

The thermistor selected for this project is a calibrated sensor. A regression curve had nevertheless to be fitted based on the data points provided in the datasheet. This was done with the function "curve_fit" of the Scipy library, and the results are illustrated in figure 1.

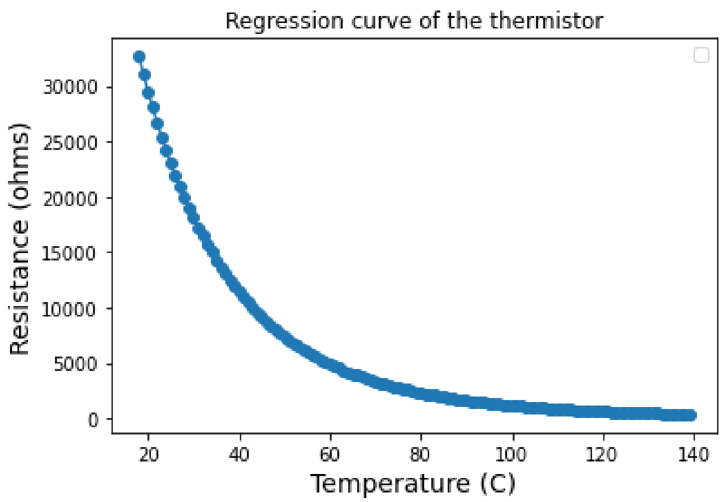


Figure 1: The thermistor's regression curve was computed as a best fit on the data points provided by the manufacturer [3].

The regression curved obtained with the library is a decreasing exponential that needs to be turned into a logarithm to infer the temperature from a resistance reading. Hence the following formula was implemented in the processing unit (i.e., in the Arduino):

$$T = \frac{-\log((R-c)/a)}{b}$$

where T is the temperature in Celsius, R the resistance in ohms, a = 31650, b = 0.04536822, and c = 434.40881.

2.2 Model of the Reem-C's hand

The Reem-C robot has a humanoid hand geometry, but most gloves on the market would not fit its bulky palm and thin fingers. A stretchable textile glove was therefore custom-made and sewed to get a better fit with its unique geometry. In a first step, the dimensions of the Reem-C's hand were measured and a model was created using Autodesk's 3D CAD software (see figure 2, available on the project's git repository [1]).

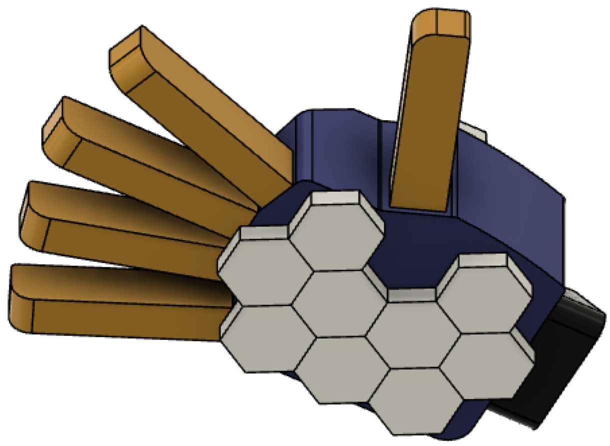
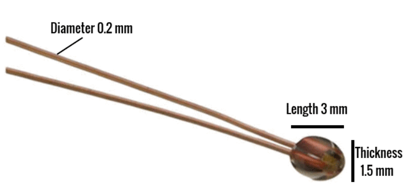


Figure 2: 3D model of the Reem-C's hand. This model helped defined the proportions of the glove.

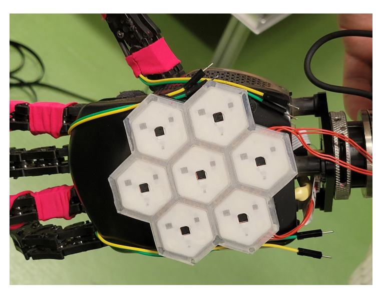
2.3 Assembly of the sensors

The temperature sensors and their wires are extremely thin and delicate (see figure 3a). Assembling them on the system was to some degree challenging. Besides, the 2 terminals were less than 0.5 mm apart at the level of the thermistor's glass envelope, which in the absence of a microscope prevented soldering close to the thermistor. To add mechanical support as well as to isolate the wires properly, tubes of heat shrinks were ran from the soldered join all the way to the thermistor sitting at the tip of the cable. Figure 3c shows two sensors fixated to the inner side of two of the Reem-C's fingers with bands of stretchable textile.



(a) Dimensions and geometry of the thermistor

(b) Sensors can be positioned on the finger



(c) Connectors of the sensors on the back of the hand

2.4 Manufacturing of the glove

Two different techniques were employed to manufacture the textile glove. Based on the 3D model, a footprint of the hand was created as a vectorized graphics file (.svg). This image was upload to a laser etching machine to automate a precise cut of the textile. This method didn't prove successful though as it could not pierce the material, most likely because because the laser was not sufficiently powerful. Besides the laser had the tendency to overheat the textile and burn it.

Figure 4: The footprint of the Reem-C's hand when sewed on textile.

The second method employed relied more on manual skills and low technology. The footprint of the robot's hand was printed on a piece of paper. This image was laid on 2 layers of textile sitting on top of each other, and I sew these 2 layers by tightly following the contour line of the footprint. The result is shown in figure 4. Holes were perforated on the palm and back of the hand to leave space for existing sensors (figure 5).

Figure 5: Reem-C's hand with the glove and temperature sensors on. The tiling of white hexagons on the palm and back of the hand provide other sensory abilities.

2.5 Temperature readings and data transmission

Readings the thermistor's varying resistance was done with the help of a voltage divider implemented with a reference of 3.3 kohms on breadboard. Each sensor required a voltage divider of its own. Without multiplexers, the number of pins on the Arduino limited the number of sensors to 4. I decided to experiment with 3 sensors in total, one for each of the Reem-C's 3 finger groups (thumb, index, and the remaining 3 fingers are grouped together for motor commands).

Once the temperature measured by each sensor is calculated, a data package is concatenated and transmitted by the Arduino over the Ethernet UDP (User Datagram Protocol) to the IP address of the receiver. In the experiments described in the following section, the receiver was my personal computer running a ROS node that publishes the temperature on a topic, but this could as well be the ROS master on the Reem-C. The different software items developed in this project are available on my github repository [1].

3 Results

3.1 The experimental setup

The experiment described in this section aimed at assessing whether or not the system could trigger a reflex behavior and pullback action in a situation where the robot reaches for a hot object that would harm it. To do this, a number of assumptions were made. The first assumption was that a contact with an object above 80 degrees Celsius for less than a second would cause severe burns to a human [6]. In this situation, the reflex should occur faster than within a second.

In order to observe the dynamics of the sensor when in presence of a harmful, hot object, I placed the sensor at different locations away from a halogen lamp 6. There was therefore no other way to measure the temperature than with the system itself, which we may consider reliable because this is a calibrated thermistor. Therefore, I reasonably assumed that the temperature reached by the sensor in the steady state is representative of the actual temperature of its surroundings. Finally, I could not control for how long the lamp would take to reach its steady state after it was turned on. If the lamp's temperature was constant throughout the trials, the sensors would have received more heat and accordingly would have responded earlier.

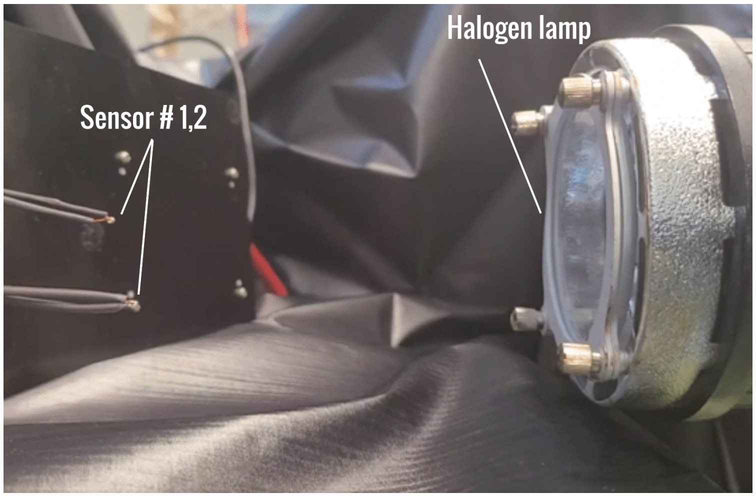


Figure 6: Experimental setup with the thermistors sitting 12 cm away from the lamp. The third thermistor was placed with the rest of the electronics behind a screen and served as control to make sure the electronics didn't suffer the effect of the heat. A video of a trial of the experiment is available here [2]: https://youtu.be/WKAtvohjQNo

3.2 Data analysis

Figure 7 shows the temporal response of the sensor when place at different locations d = (8, 10, 12, 15, 20) cm away from the halogen lamp. During each of the 5 trials, 2 sensors were exposed to the light and the third one was not and served as control. This explains the five curves that remained below 60 degrees throughout the trial. Among the 2 sensors exposed to the light, the response and the steady state vary considerably, which suggests that the field of radiating heat is not uniform and that distance from the light isn't a reliable experimental factor. In general, all curves exhibit an exponential and asymptotic behavior as expected. Further data analysis shall focus on the steady state as the controlled experimental condition.

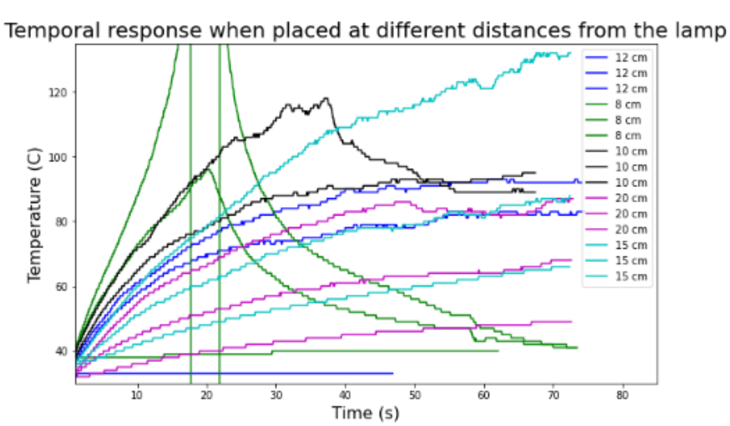


Figure 7: Temporal response of the sensor over 70 seconds of exposure to the heat.

In figure 7, all trials were aligned with one another at t_0 = t_onset when the light was turned on. The exposure to the heat lasted approximately 70 +/- 5 seconds, which was sufficient to reach the steady state. The nominal temperature of the sensor varied from 31 to 38 degrees because sensors didn't always have enough time to entirely cool down, and the hot temperature in the lab didn't help. During the trial when d = 8 cm, the temperature measured by a sensor seems to have gone beyond the normal range of operations, and the sensor made noises. During the following trial, the sensor seemed unreliable, and I replaced all sensors to pursue the experiment. Besides, the logarithmic function returned 0, probably because its argument was close to 1, which might be explained by the fact that I fitted the curve with values up to 140 degrees (see figure 1). The light was turned off after 20 seconds, and this was not investigated further.

In order to assess in which way the system could trigger a reflex behavior within less than a second, I computed the derivative of the sensor's response during the first few seconds of each trial (see figure 8). Because most human organs act on the detection of relative changes in their environment, biologically-inspired reflex mechanisms might be best triggered by drastic changes in temperature over a short period of time. This rationale guided the rest of the analysis.

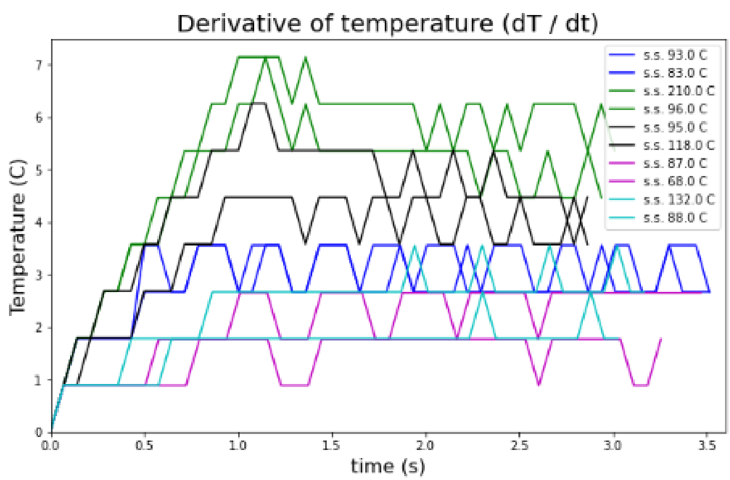


Figure 8: Rate of change of temperature over time.

In figure 9, the mean rate of temperature change was computed over the first half second of exposure to heat and plotted as a function of the steady state reached by the sensor, which is considered to be a proxy for the actual temperature of the environment or object in the vicinity of the robot's hand. This figure shows a positive correlation between the variables, which indicates that, when the robot comes in the close vicinity of objects above 80 degrees, a signal based on the rate of change of temperature could be triggered within much less than a second to pull back the hand and avoid more serious injuries. The data shows outliers during the conditions 87 and 88 degrees at the steady state, which might be explained by the non-uniform field of radiating heat or by a higher nominal temperature.

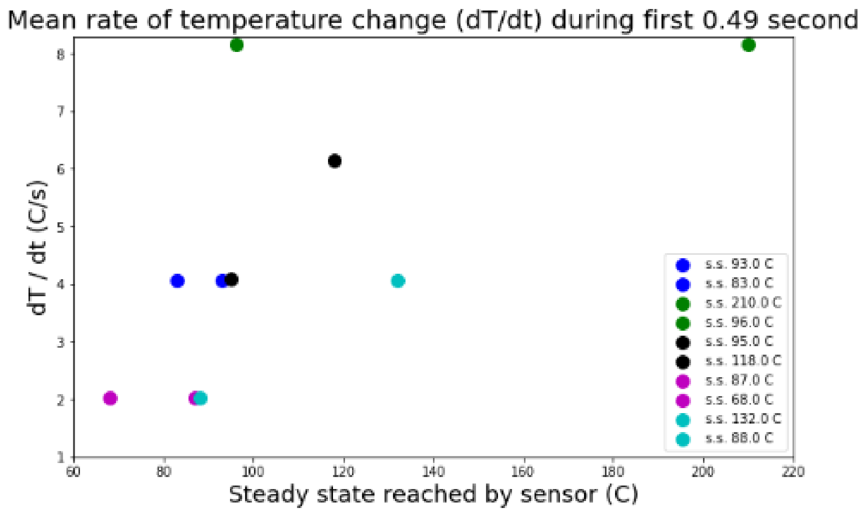


Figure 9: Mean rate of change of temperature during first 0.5 seconds.

4 Discussion

The system designed in this project as well as the tests performed with it have shown that it is feasible to generate a reliable signal and trigger reflex behaviors with the help of low latency thermistors integrated into a robot's hand and transmitted over a standard Ethernet protocol. This signal could be based on the rate of change of temperature in a fashion similar to how some biological sense organs respond to relative changes in their environment and not to absolute temperature values. The experimental conditions under which the system was testing could however not be entirely controlled, as indicated in the previous section. Hence further work in this area would require more controlled and reproducible experimental conditions to investigate the temporal response of the system. Besides, end-to-end latency in a full integration with the robot should be assessed.

Among the remaining questions to answer is whether the same results can be obtained if the thermistors are embedded in a silicone matrix with no direct contact with the air. Such a construction could be necessary if one wished to procure more mechanical stability to the sensory system like the human skin layers dermis and epidermis do. One would also like to find out whether the thermistor's wires could easily break as a consequence of repetitive contacts with hard objects, during prehension or as a result of other behaviors involving the hands. To avoid this, it could be worthwhile to use the cavities the Reem-C's fingers offer (the fingers are to some degree hollow, see 3c) and position the sensors rather slightly inside than on the fingers. On the other hand, hiding the sensors in this fashion might prevent them from sensing the radiating heat, and an architecture such as in [10] could be more robut. Hence a balance between the number of sensors and their position might be required.

5 Conclusion

5.1 Concluding remarks

When it to temperature sensing and contact with hot objects, a robotic arm or prosthetic must be able to respond fast to avoid damages and injuries. This project showed how thermistors can be used with ROS-based robotic systems to trigger reflex behaviors.

My project started off with the intention of adding multiple sensory modalities to the glove. These included force sensors to add a sense of touch and flexion sensors to add sensory feedback to the control loop sending finger motor commands. The sensor search and literature review I performed covered flexion sensors as well, and a capacitive sensor was even selected and purchased (see [5] and [8]). While this part of my project didn't lead to outcomes as definite as those shown in the previous sections, it nevertheless introduced me to various aspects of robotic systems that I might consider when working on my thesis next year.

Besides adding other sensory modalities to the glove, an important milestone remains to develop a scenario in Gazebo, a 3D simulator for robotics. In the course of my project I actually allocated many hours to trying to achieve this. While I could not conclude with a functional simulation, this excursion resulted in the completion of a number of other learning outcomes: set up an earlier version of Ubuntu as a virtual machine with Docker, overview and use of some ROS packages to simulate and control the Reem-C, knowledge of Simple Action Clients and how they are used to define a path and set of motor commands.

5.2 Special thanks

I would like to thank my supervisor Dr.-Ing. John Nassour for his availability, continuous presence, joyful contributions, and constant sharing of creative ideas. Besides him I would also like to thank Fengyi Wang for his co-supervision and Simon Armleder and Dr.-Ing. Julio Rogelio Guadarrama Olvera for their support while I was trying to do simulations with the Reem-C.

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