ROBOTIC ARM – FORCE SENSITIVE

SENSOR DESIGN PROJECT REPORT

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BME 462

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Abstract

This report goes over the process of designing a force sensitive robotic arm, that could assist remote operators during robot-assisted surgeries to be sensitive to force applied on tissue. The report goes over FDA classification, design consideration for both hardware and software, testing for verification and validation of device operation.

Device Description

Medical Instrumentation

Robot-assisted surgeries have been gaining ground for the past few years. For nonautonomous systems, such as the da Vinci robot, a remote operator is in control of the system in a master/slave configuration [1]. With such systems, there are clear advantages, like the use of miniature tools, stability, and precession of movement, but also clear issues that need to be addressed. One issue is that without proper feedback loop, these robotic arms cannot sense how much force is exerted on the tissue manipulated. Therefore, specific sensors must be mounted on those robots so that the operator can have a sense of the tool-tissue interaction in place. Here I describe the process of designing a crude prototype using a simple plier, sensing circuit, and C++ based code in MBED environment.

Intended Use

The device could be considered both therapeutic and diagnostic depending on the nature of the operation. For the purposes of this report, I considered the device to be of a therapeutic nature as it is intended to assist remote surgeon in grasping action during minimally invasive surgeries. However, such sensor could be mounted on different attachments for diagnostic purposes while keeping track on tissue-tool interaction in various endoscopy procedures [2].

FDA Classification

Based on the FDA database for biomedical devices classification, endoscopic robotic arms are classified under class II devices [3].

Hardware/Software Description

Hardware Block Diagram

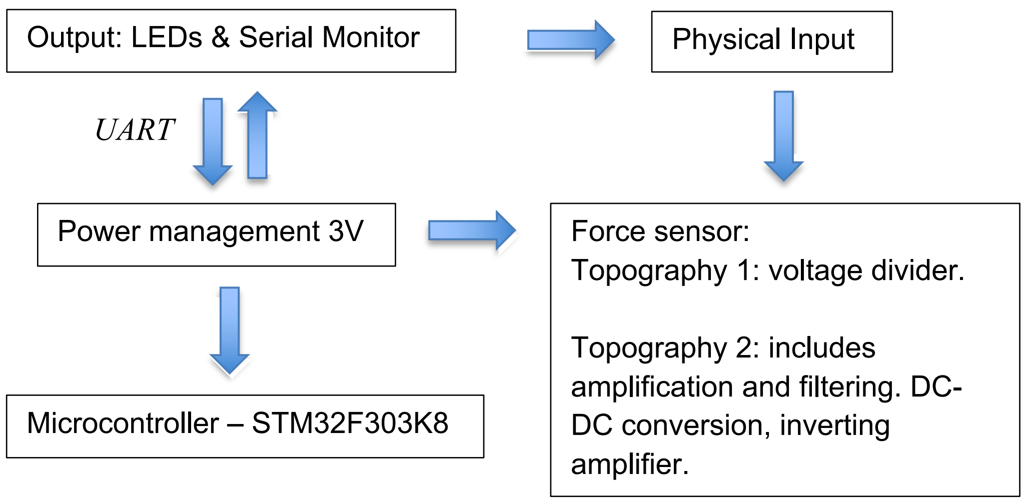

Figure 1. *hardware block diagrams showing the flow of information between the components of the system. From the user input through the negative feedback influencing the user.*

Software Block Diagram

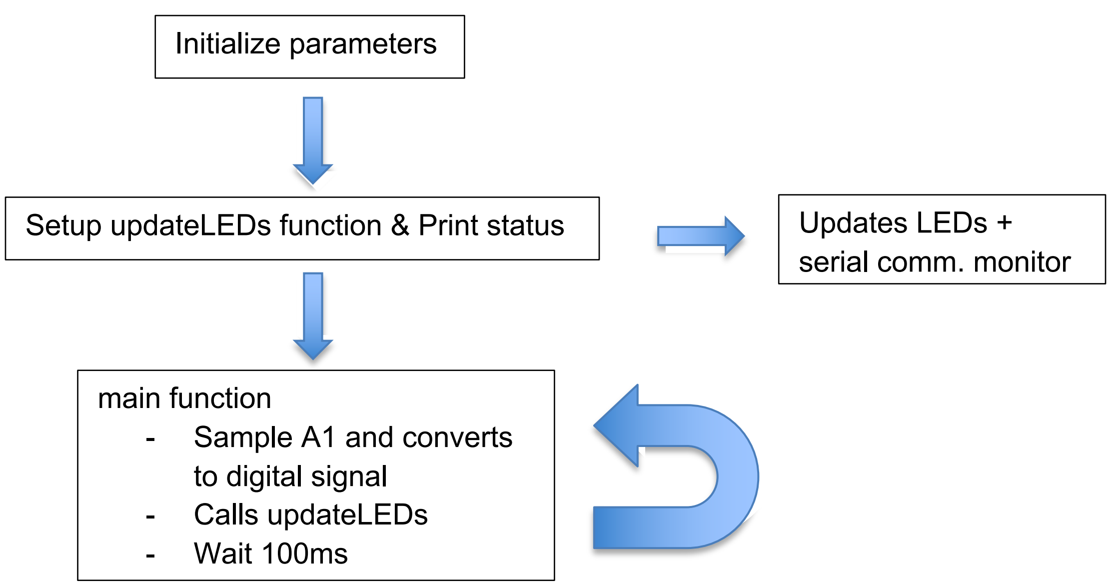

Figure 2. *Software block diagram following the logic of the running MBED software. See appendix 2 for the full code.*

Verification & Validation Testing

Mathematical Equations

$$Vout = Vin * \left(\frac{R2}{R1+R2}\right) \longrightarrow R1 = Vin * \frac{R2}{Vout} - R2\ ,\ R^2 = 1 - \frac{RSS}{TSS}\ ,\ Resoluation = \frac{\Delta Vout}{\Delta Force}$$

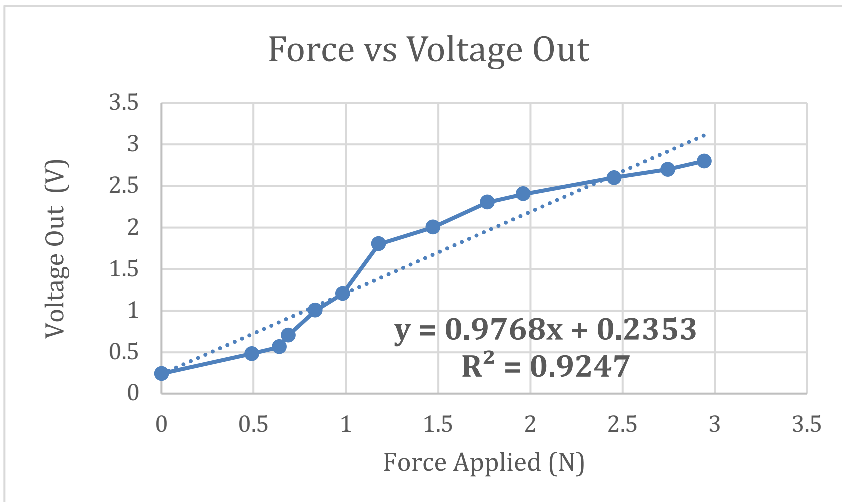

Figure 3. Demonstrates the calculations performed in Excel based on the values obtained in the calibration process. Resolution 0.97V/N.

Given the R squared value, we can be confident the sensor gives accurate readings of exerted force. Of course, such confidence is within the specific range of forces calibrated. Meaning, the target range should be identified before the execution and another specific calibration process should take place.

$DC - DC\ converter + inverting\ op.amp\ and\ cutoff\ frequency$. *See Appendix 3 & 4.*

$$F_C = \frac{1}{2\pi RC} \qquad Vout = -Vref * \left(\frac{Rf}{Rs}\right)$$

For the second topography which include a dc-dc converter, and an inverting amplifying stage, specific parameters can be tweaked to achieve different sensitives to different tasks. From the formulas above, I chose to use a 300pF capacitor in parallel of a 10kΩ resistor to achieve ideal amplification and a low pass filter to remove high frequency noise that might confound the feedback. Furthermore, the driving voltage can be modified using a voltage divider or another op amp to down amplify the coming signal.

Requirement Name	*Status*
Safety	*This device is a minor extension that will be embedded in existing validated technology; therefore, safety standards should be met with ease. The code and LEDs can be modified such a certain threshold will illicit alarming feedback. For example – RED LED.*
Accuracy and Versatility	*From the validation process, the device worked with 92.5% accuracy and with great versatility. The device performed well with different components giving it different sensing ranges with high degree of resolution.*
Feedback	*Visual feedback was successfully incorporated into the design in two forms: LEDs of different colors and a serial pc communication.*
Storage	*Given the UART protocol, sensing data can easily be recorded for later analysis and comparison with surgical outcomes and potential tissue damage.*

Table 1. *Summary of user & design requirements in the validation process.* Based on the desired application and force that is typically exerted during retraction with grasping in general surgeries [2], the system is sensitive to desired forces in the range of 1-3N. This range was chosen so that system could produce feedback with high sensitivity.

Conclusion and Future Work

From testing and validation process these force sensors are great candidates for achieving high precision and reliable source of information with respect to forces exerted on objects. Overall, each step in this process was in line with the previous one. From the first mathematical approach to the LTspice simulation and physical testing, the system behaved as expected [see appendix 1]. Force was measure successfully, and the microcontroller produced expected and appropriate feedback. However, a more complicated discussion should take place when such objects in question are malleable. Furthermore, the pad of the sensor needs to be characterized for different force sensitivities. If an object does not have a flat profile, unlike the objects used in the testing here, the sensor might not reflect the true force exerted on tissue.

For the purposes of this level of investigation, I would improve one minor issue, which was the indirect calibration process which took place. Instead of finding the relationship between force exerted and change in resistance using a multimeter, I looked at change in voltage via an oscilloscope. Lastly, it is conceivable that any penetrating object during invasive surgeries could use such sensors even if the operator is working directly with tissue. Further force sensors for different degrees of freedom could be incorporated to obtain more comprehensive data collection.

References

[1]
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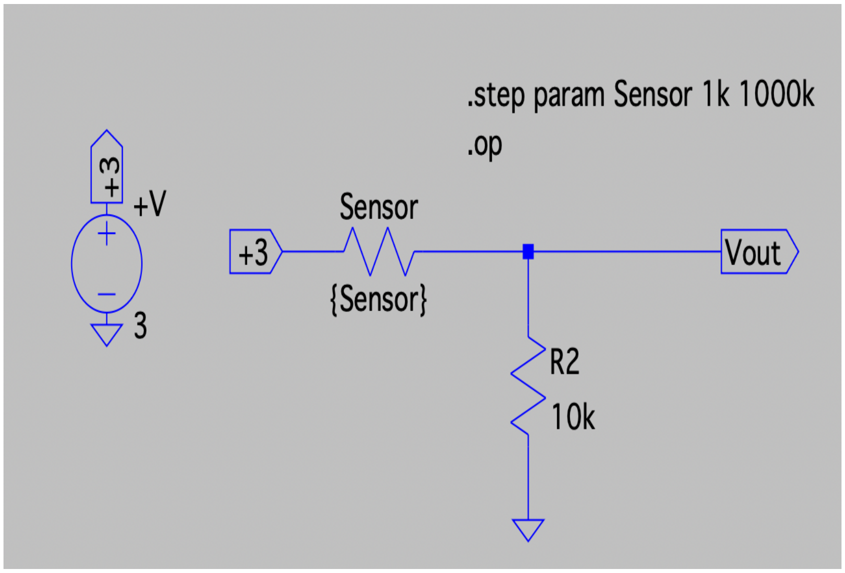
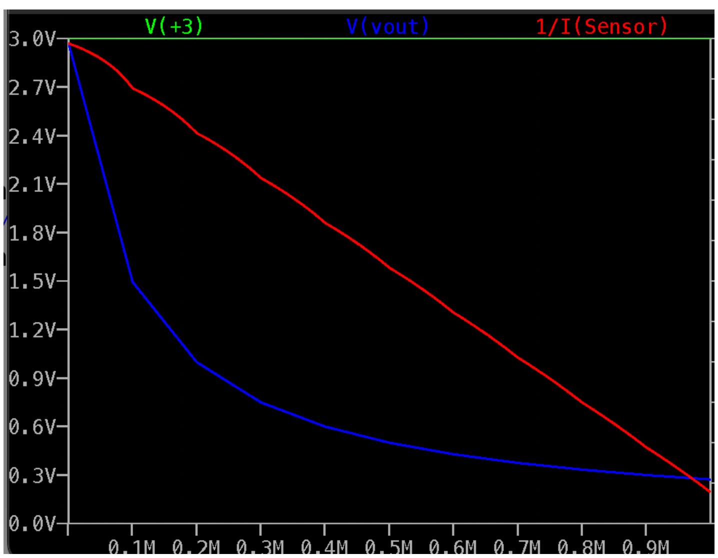
Appendix

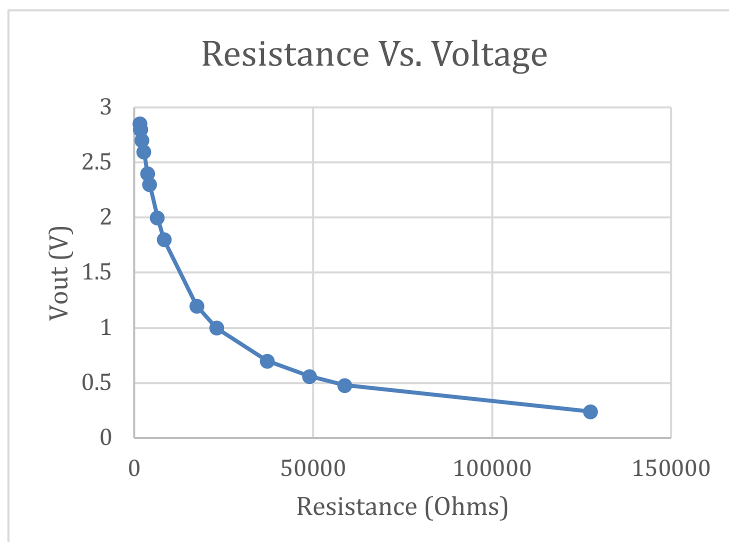
A.



B.



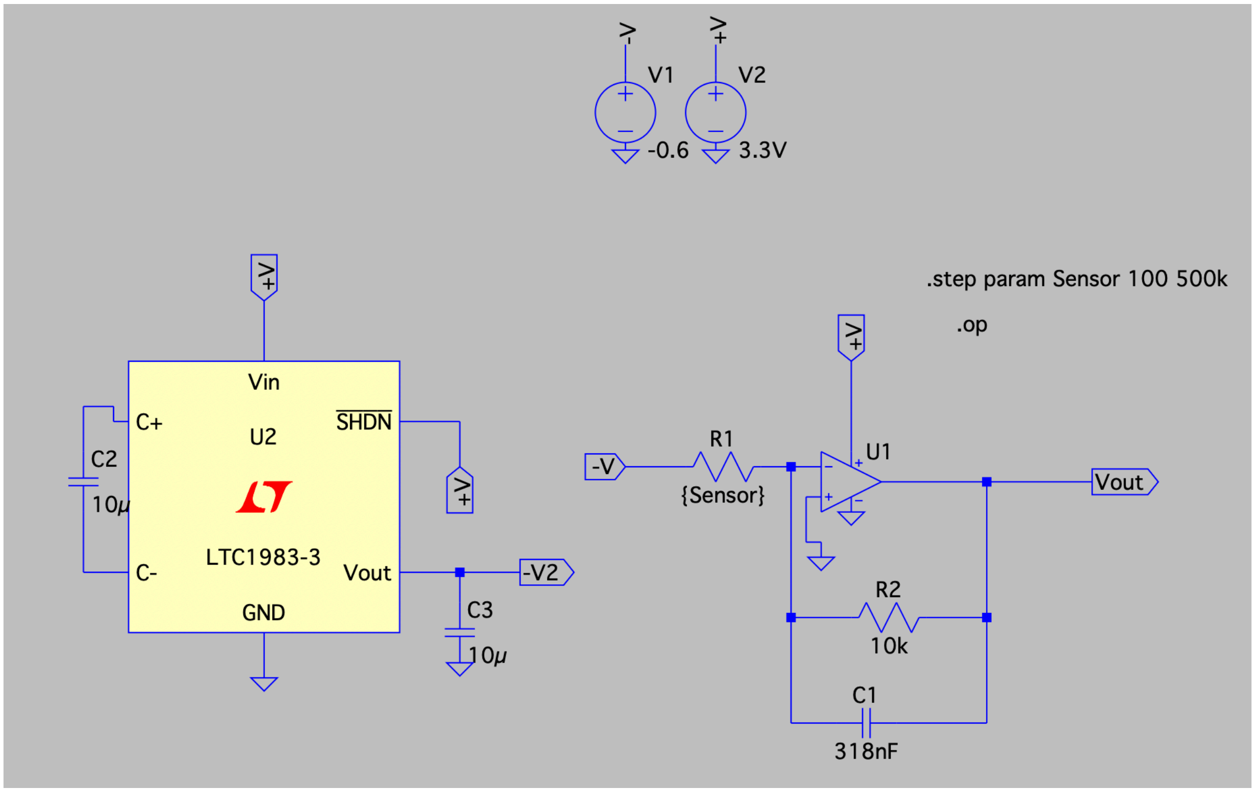
C.



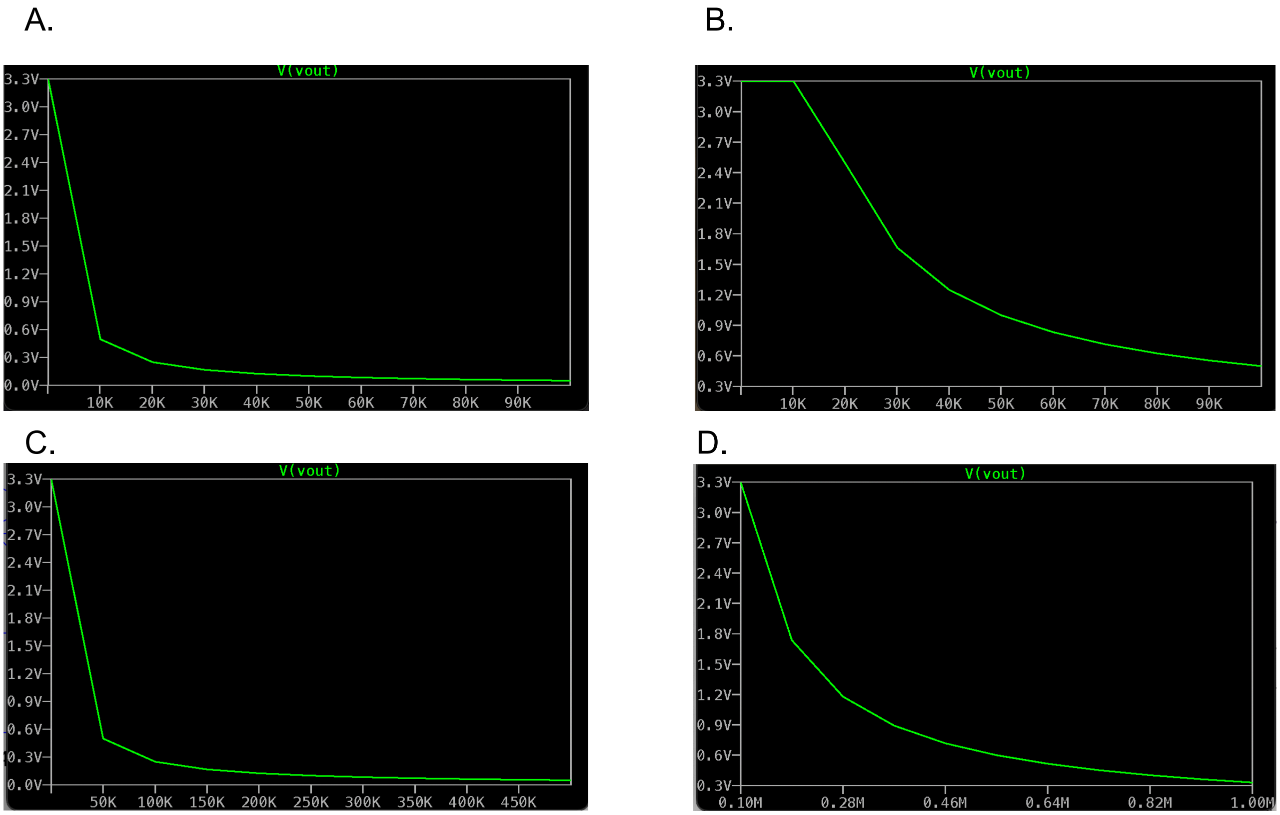
Appendix 1. A. demonstrates voltage divider schematic which gives rise to the above equation. B. displays a sweep in LTspice of sensor resistances between 1MΩ and 1kΩ. C. displays a verification of expected exponential curve between resistance of sensor and voltage output in high correspondence to computer simulation.

```
force_project > main.cpp > ...
#include "mbed.h"

DigitalOut leds[] = {D7, D8, D9, D10, D11, D12}; // Initialize DigitalOut objects
AnalogIn analogInput(A1); // Initialize AnalogIn object
BufferedSerial pc(USBTX, USBRX); // Initialize BufferedSerial object for communication

// Function to update the LEDs based on the digital value and print status
void updateLEDs(int digitalValue) {
    leds[0] = 1;  // Set D7 to on

    // Determine the number of LEDs to turn on based on the digital value
    int ledCount = digitalValue / (1024 / 6);  // Divide by 171 (1023/6) to get a range of 0 to 5

    for (int i = 1; i < 6; i++) { // Turn on additional LEDs based on the digital value
        leds[i] = (i <= ledCount);
    }
    // Print the digital value and the number of LEDs on to the serial terminal
    char buf[50]; // Ensure the buffer is large enough to hold the entire string
    sprintf(buf, "Digital Value: %d, %d LEDs On\r\n", digitalValue, ledCount + 1); // +1 including D7 which is always on
    pc.write(buf, strlen(buf)); // Directly write formatted string
}
int main() {
    pc.set_baud(9600); // Set baud rate for serial communication

    while (true) {
        // Read the analog value and convert it to digital value
        int digitalValue = analogInput.read_u16() >> 6; // Convert to 10-bit digital value

        updateLEDs(digitalValue); // Update the LEDs and print status

        ThisThread::sleep_for(100ms); // Small delay for stability
    }
}
```

Appendix 2. Code imported into the microcontroller from the Keil Studio Cloud. The most important aspect of it is that the user can change the cutoffs for turning on LEDs to componsate for some limitation that might be present in the hardware. Yes, the resolution might be impaired, but with high enough of resolution, the device can function well even without the full range of voltage.



Appendix 3. Hardware schematics in LTspice of the second iteration of the circuit. With this topography, one can use the low pass filter to get rid of unwanted noise. Furthermore, with two parameters influencing the amplification, there is a greater level of control on amplification and better range of possible forces.



Appendix 4. A. 10k ohm R2 – greater sensitivity for larger forces. B. 100k ohm R2 – greater sensitivity at lower forces. C. Vref = -0.25v greater sensitivity for larger forces. D. Vref = -3.3v greater sensitivity at lower forces. Overall, this verifies that sensitivity can be modified using two parameters to achieve greater user flexibility.

Appendix 5. Crude prototype for plier style attachment for blood vessel clamping procedure in invasive surgeries. Testing videos can be viewed on YouTube. Link supplied throughout respective segments in the presentation document.