MTHE 393 Group 17 Final Report

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Contents

1 Introduction

The goal of this project is to design a controller for a black box system that will meet certain performance specifications. These specifications include the rise time, steady state error and settling time of the system. In order to begin designing a controller, a transfer function for the system must be obtained. To do this, the team first needed to de-noise the output signal from the black box so that certain properties of the system could be determined. The de-noising of the system was done using the combination of the Butterworth and the zero-phase digital filters in MatLab. Once a clean signal was obtained the team was able to verify certain properties about the system, specifically that it was linear and time-invariant. From here, bode plots of the system were constructed by running the system at various frequencies using a sine input function. The goal of constructing bode plots was to begin the process of estimating a transfer function that describes the system's behaviour. Using that information, the team was then able to design a controller in order to meet certain target criteria for the system's response to a step input while ensuring IBIBO stability. The team has also related the controller design to the real world application of robotically-assisted surgeries. A complete analysis was conducted on the application starting by considering current codes and standards to ensure legal compliance. Then a triple bottom line analysis and an economic analysis were performed to determine a list of constraints for the controller design.

2 De-noising

Beginning with denoising, an unfortunate downside to the black box system provided is that the output function generated contains a substantial amount of noise. One of the most common methods to remove noise from a signal is to apply a filter to it. The MatLab application has many built-in filter functions and therefore an appropriate filter must be selected.

The first step in choosing a filter involves analyzing the noise of the output function. After playing around with the GUI for some time, it was observed that the noise generated on the output signals was of a high frequency relative to output function's apparent frequency. For this reason, a low-pass filter was chosen because it will block out the parts of the output signal with high frequency properties. To save computational time and simplify the filter, an infinite impulse response filter (IIR) was selected over its finite counterpart. With these specifications, MatLab recommends the following filters [3]:

- Butterworth IIR filter
- Chebyshev type 1 IIR filter
- Chebyshev type 2 IIR filter
- Elliptic IIR filter

Comparing the frequency response of these four filters in Figure 1, we see that the Butterworth filter has the slowest roll-off. However, this roll-off can be sharpened by increasing the filter's order. The Butterworth filter's frequency response is the only filter to show no ripples which is important for creating the smoothest possible filtered function. As a result, the Butterworth IIR low-pass filter was selected for this project.

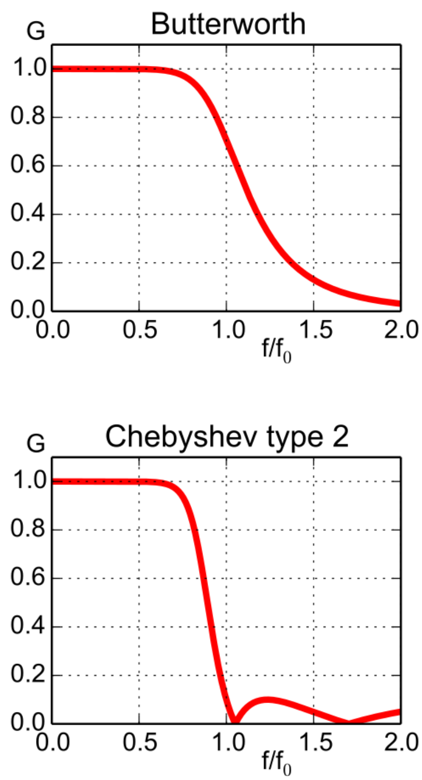


Figure 1: Frequency response of the recommended MatLab filters, all with 5th order [4].

In MatLab the Butterworth filter function takes three input arguments and outputs the coefficient matrices for the numerator and the denominator of the filter's transfer function. The first argument is the filter order which specifies the sharpness of the filter's roll-off. As the order increases, the roll-off becomes steeper and therefore less frequencies pass through the filter. The second argument is the cut-off frequency which specifies which frequencies will pass through the filter. The last argument is filter type which has already been specified to be the low-pass filter [2]. These arguments can and should be adjusted based on the overall frequency of the black box's output function.

As an example consider the function $f(t) = 2sin(10t)$. Selecting an order of 3 and a cutoff frequency of 0.007 creates a good approximation as shown in Figure 2.

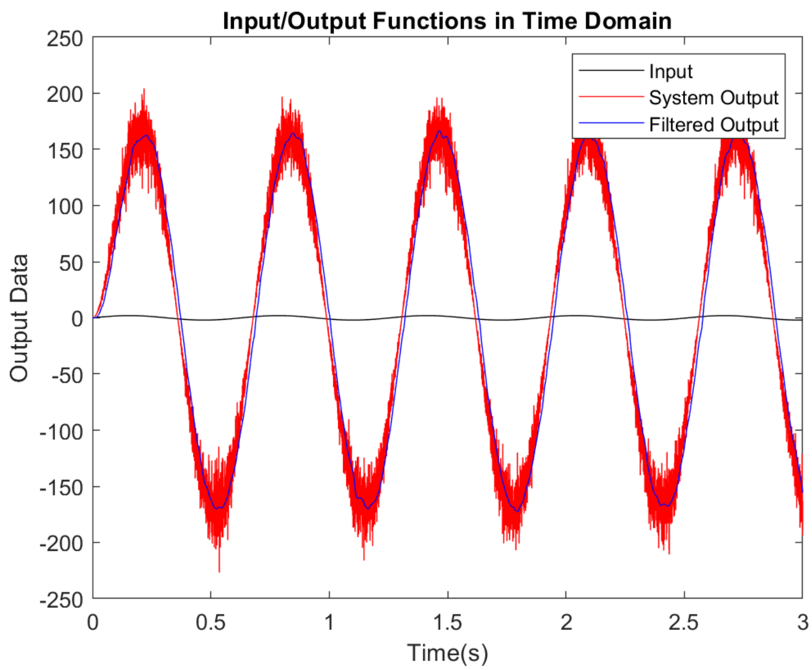


Figure 2: System input of $f(t) = 2sin(10t)$, system output, and Butterworth filtered output overlayed.

In a perfect world, increasing the order and decreasing the cutoff frequency should give a more filtered function. However, due to the properties of the Butterworth filter and its corresponding transfer function, making these changes can apply a time shift to the filtered signal, making it less accurate. Note that this filter can applied to functions other than the sine function. Figure 3 demonstrates that the Butterworth filter still works effectively when applied to the output of the system given a piecewise input signal.

In order to further prevent any errors that result from a time shift of the filtered signal, a zero-phase filter was applied in MatLab to this already filtered signal. The zero-phase digital filter in MatLab takes three input arguments. In this case, these arguments were the coefficients of the numerator and denominator of the Butterworth filter's transfer function and the original noisy signal. This input signal is then filtered in both forward and reverse directions so that there is zero phase distortion in the result [1]. The purpose of doing this was to ensure that the data recorded for the phase difference bode plot was not impacted by the use of the Butterworth filter. A signal that has been filtered

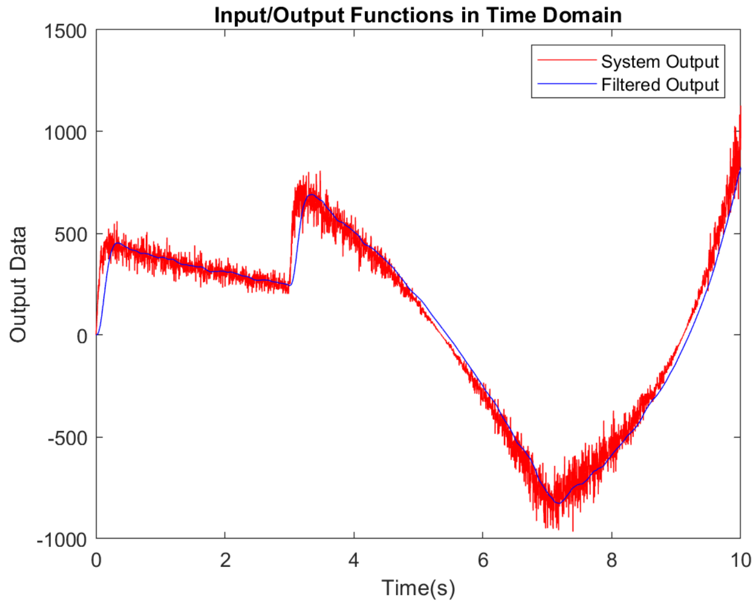


Figure 3: System output and Butterworth filtered output overlayed given a piecewise input.

using the zero-phase digital filter can be seen below in Figure 4.

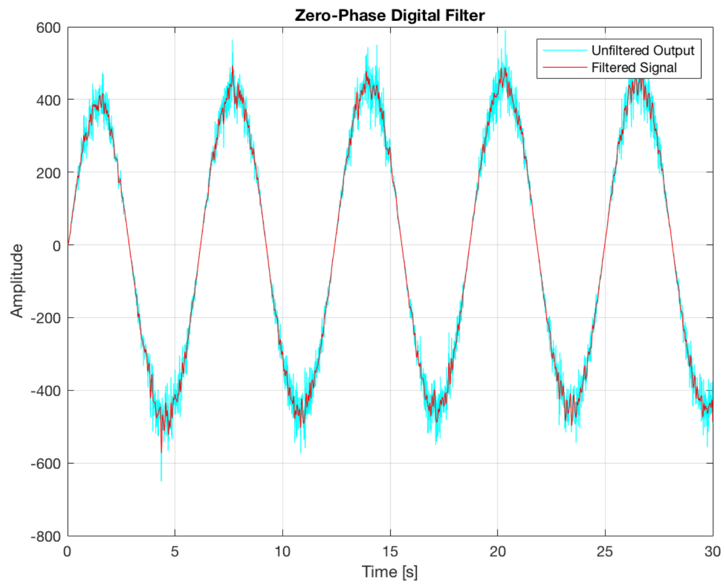


Figure 4: System output and Zero-Phase filtered output overlayed using sine input.

3 Verification of Linearity and Time-Invariance

After removing most of the noise appearing in the output behaviour of the black box system using the Butterworth filter, the next task was to verify that the unknown system is indeed linear and time-invariant. The reasoning is that having these two properties allows for the modelling of the system by its transfer function in the frequency domain. This provides a rigorous and mathematical way of analyzing the relationship between the input and the output behaviour of the system rather than merely observing the output behaviour for each input.

The most logical place to start would be to consult the definition of linearity and time-invariance of a system [5].

A system Σ is linear if the following two conditions are satisfied:

1. $\Sigma[ax(t)] = a\Sigma[x(t)]$ for all a $\in \mathbb{R}$ and input signals x(t)

2. $\Sigma[x_1(t) + x_2(t)] = \Sigma[x_1(t)] + \Sigma[x_2(t)]$ for all input signals $x_1(t)$ and $x_2(t)$

In other words, one can verify that the system is linear if 1) the output of the scalar multiplication of the input is equivalent to the scalar multiplication of the output with the same input 2) the output of the sum of the two inputs is equivalent to the sum of the outputs for each input.

Moreover, a system Σ is time-invariant if:

$\Sigma[x(t - t_0)] = y(t - t_0)$ for all times t_0 and input signal x(t), where $y(t) = \Sigma[x(t)]$ denotes the output of the system due to x(t).

In other words, one can verify that the system is time-invariant if a time-delay of the input directly corresponds to a time-delay of the output.

It is nearly impossible to directly prove that the above conditions hold due to fact that the internal details of the system are completely unknown. Therefore, an empirical approach of observing the input-output behaviour of the system was considered instead. To illustrate this process, consider a square wave of the following form:

$$\begin{cases} 10 & a \leq t \leq b \\ 0 & else \end{cases}$$

Note that all the plots presented for this section have already been de-noised using the Butterworth filter from the previous section.

First we show that the system is linear. Figure 5 shows that the output of a scaled input square matches the scaled output of the original input by the same factor. Moreover, Figure 6 shows that addition of the two outputs using different input square waves matches the output of the sum of those same input square waves.

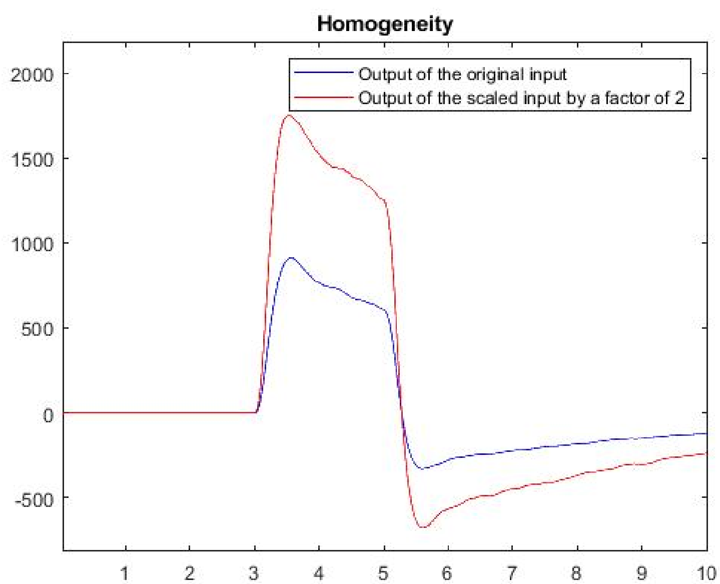


Figure 5: Homogeneity of the black box system shown with an input square wave with amplitude 10 with a scaling factor of 2

Next, we show that the system is time-invariant. Figure 7 shows that the output of the shifted input square wave matches the output of the original input shifted by the same phase.

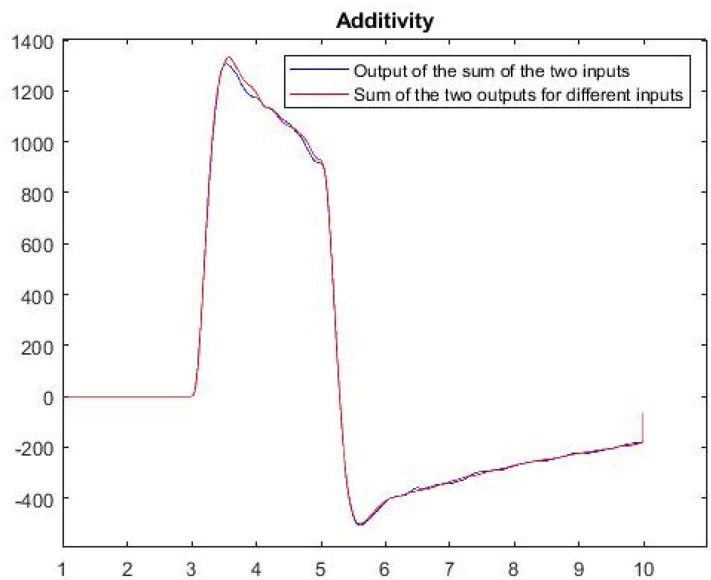


Figure 6: Additivity of the black box system shown with two input square waves with amplitudes 5 and 10

The above results provide a good reason to believe that the system is indeed linear and time-invariant. Moreover, having this validation allows us to proceed with further analyses of the system which are discussed in the upcoming sections.

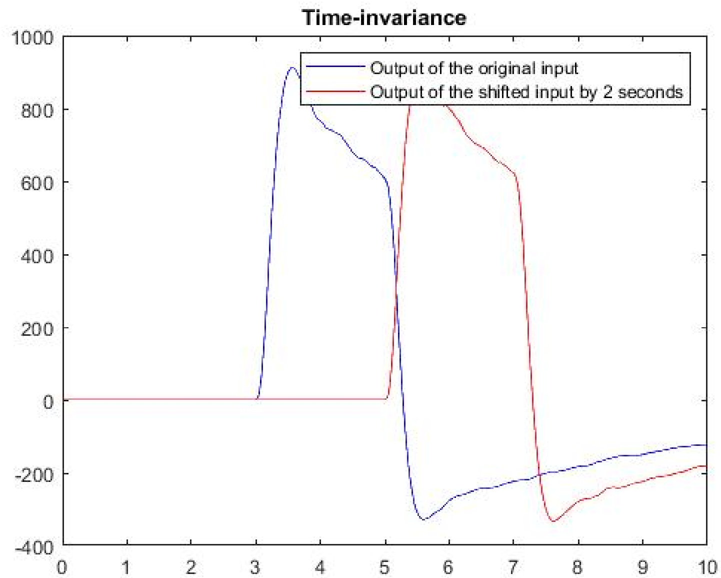
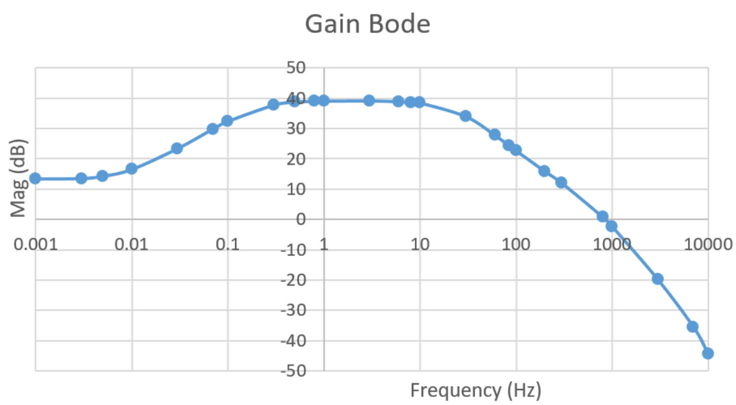


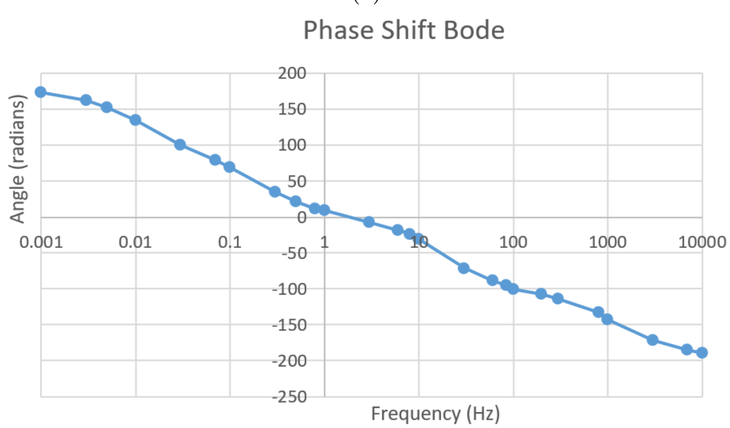
Figure 7: Time-invariance of the black box system show with an input square wave with amplitude 10 during 3-5 seconds and 5-7 seconds

4 Bode Plots

As mentioned in the previous section, having the transfer function in hand allows one to infer the system's behaviour over possible inputs without knowing the complete details of the system. This allows the team to design controllers to steer the system to meet the system targets. To construct the transfer function the team first needed to construct Bode plots of the system. These plots show the gain and the phase difference of the system from an input function at various frequencies. As previously mentioned, MatLab was used to filter the output of the system so that accurate magnitude and phase shift readings could be obtained. To obtain the plots the black box system was run 25 times with the function $2sin(\omega t)$ and frequencies varying from 10^{-3} to 10^{4}. The functions were then saved to MatLab and run through the filtering algorithm. The resulting filtered signals were then plotted against the input sine wave. From here the magnitude of the signal filtered using the Butterworth filter was recorded. The phase shift was calculated by using the zero-phase filtered signal and taking the time difference at $y = 0$ between this filtered signal and the input function. The time difference was then multiplied by the frequency to get the phase shift in radians, which was converted to degrees for the sake of the plots. These values were recorded at all 25 frequencies in an Excel spreadsheet and were then plotted on a logarithmic scale to obtain the Bode plots. We see these plots below in Figures 8a and 8b.



(a)



(b)

Figure 8: Bode Plot for BlackBox System (a) Gain Plot (b) Phase Plot

In the bode plots above we see that there are points of inflection approximately at the frequencies: 0.01, 0.2, 20, 110, and 1200 Hz. These points of inflection are most clearly visible in the gain plot. However, these inflections line up with the slight variations of slope that can be seen in the phase difference plot. The phase difference plot seen here was confirmed by using the original noisy output signal to construct another one. At $y = 0$ the noisy output signal was a straight line and so time difference data could be taken to build another phase difference plot to confirm the result. The process used to construct this plot was the same as the one described above.

5 Transfer Function

Now that the points of inflection have been identified along with the corresponding frequencies, a transfer function can be inferred from the plots. The best way to do this is to note that roots of a transfer function cause an increase in slope of 20db/dec and poles of a transfer function cause a decrease in slope of 20db/dec. Analyzing the slope of our gain bode plot in Figure 8a around the points of inflection allowed us to determine an approximation of the transfer function. Plotting the Bode plots of this transfer function on the same axis as our experimental Bode plots allowed us to fine tune the locations of the zeros and poles as well as their sign in order get a perfect match. This graph can be seen in Figure 9 and implies our transfer function is a good approximation.

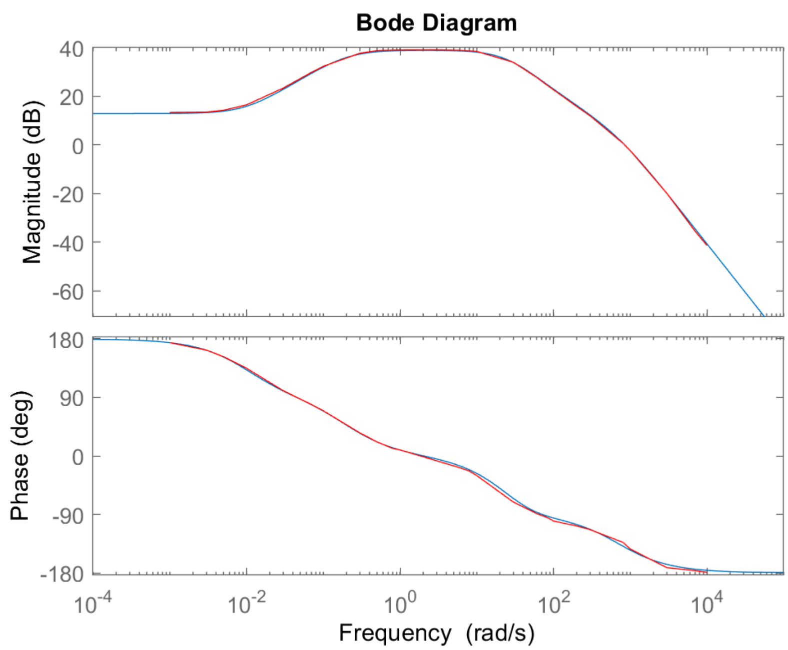


Figure 9: MatLab generated Bode plots from transfer function (blue line) and experimental Bode plots (red line).

The final equation for the transfer function can be seen below.

$$T(s) = \frac{935406(s - 0.01)(s + 60)}{(s + 0.2)(s + 30)^2(s + 700)}$$

The transfer function was again verified by comparing its step response to the step response of the black box system. The step response corresponds to the system output given the input function $f(t) = heaviside(t)$. The step response of the transfer function can be seen in Figure 10. The output of the black box system was first filtered and then plotted on the same graph. As one can see, the step responses in Figure 10 are very similar and hence the transfer function described represents a good model of the black box system.

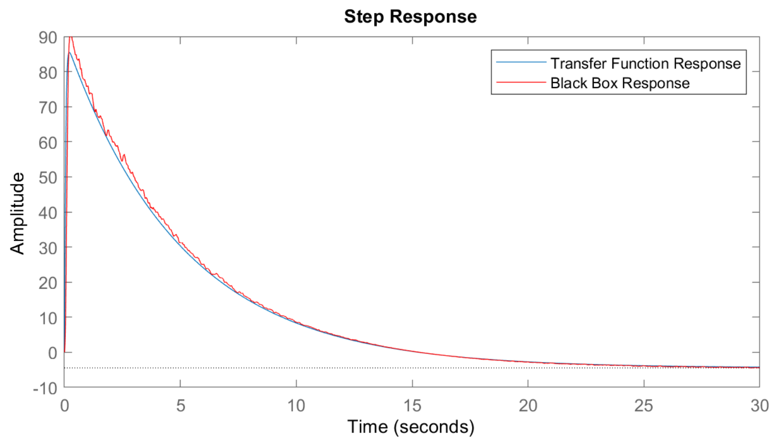


Figure 10: Step response of transfer function.

6 Controller Design

Up until this point, we have managed to come up with a transfer function that heuristically models our unknown system ('modelled dynamics'). Since our goal is to steer our black box system into meeting the prescribed system targets below, we want to design a controller that allow us to do so.

System target	Target value
Steady-state error	0.02
Rise time (s)	38
Overshoot	0.4
Settling time (s)	57
Settling time (ϵ)	0.02

The most logical place to start was to first design a controller for our proposed modelled dynamics since we know all of the necessary details about the system to study its stability upon the implementation of the controller. Then with the understanding that our transfer function mimics the behavior of the original black box system with minimal error, we can then apply the controller to the unknown system in order to fulfill the system targets.

The PID controller is the standard approach for its simplicity and effectiveness. As well, it is highly applicable for the goal of this project as PID controllers are only applied to the input/output behavior of the system, and they can be implemented without knowledge of the state behavior or the internal details of the system.

6.1 Finding the right PID values

The main goal is to fine tune the PID values that ultimately ensure that 1) the controller successfully drives the system to meet the prescribed functional requirements and 2) the modelled dynamics and closed loop are both stable.

The process began with a search for a PID controller which would meet the requirements outlined in the above table. To better observe the system's behaviour, a filter was applied to the output after the black box, as shown in Figure 11. Note that the filter was placed inside the closed-loop in such a way so that both the observed output and the sum block calculating the error signal were being fed the filtered black box output.

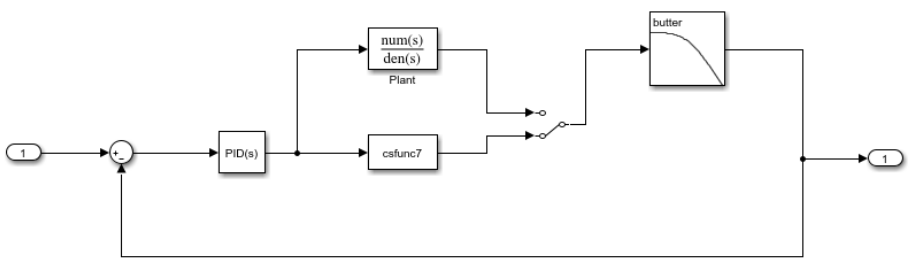


Figure 11: Simulink setup of closed-loop system design showing location of filter placement.

The filter used was a first-order low-pass Butterworth filter with a passband edge frequency of 0.6 rad/s. This frequency was determined in the next section to be within the range required to reduce the noise enough to keep the output within the steady-state error targets. Since the system was being designed to respond to a step input, altering this metric should not affect the frequency content of the reference signal being taken, as the step function is not a periodic function.

It did not take a significant amount of time for the team to find a controller which satisfied the desired rise time, settling time, steady state error and overshoot targets. This controller and the system's corresponding step response are seen in Figure 12. However, as shown, further simulation revealed that while the system would remain within the steady state targets for a long time and appeared to be stable, the output would always diverge from the reference signal eventually. In isolation, altering P, I and D did not seem to resolve this issue. In fact, the inclusion of any integral control at all would cause the output to diverge from the reference signal. This is most likely a result of the transfer function of an integral controller being composed of a gain constant over a pole

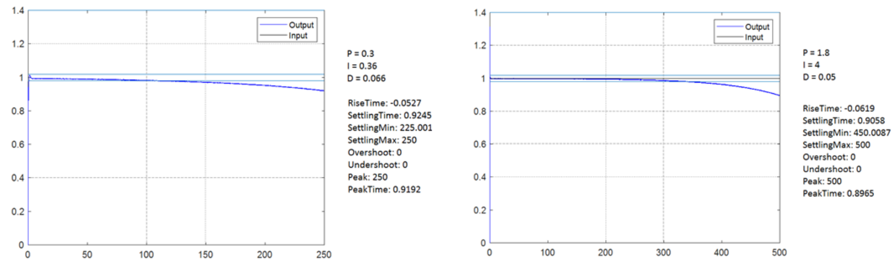


Figure 12: Step responses falling nicely within the design constraints, but diverging from the reference signal.

at s.

$$T_{C_I} = \frac{K_I}{s}$$

The inclusion of integral control in the controller's transfer function generates a root s in the denominator of the closed-loop transfer function, which results in the closed-loop system to be not IBIBO stable since this zero lies on the imaginary axis [7]. Moving forward with the requirement that $I = 0$, finding a PD controller that could steer the system output to the reference signal while also meeting all system targets proved to be an unlikely task. No values of P and D were found that could steer the system toward the reference signal within the desired targets, leading the team to look for other tools to use in conjunction with the controller.

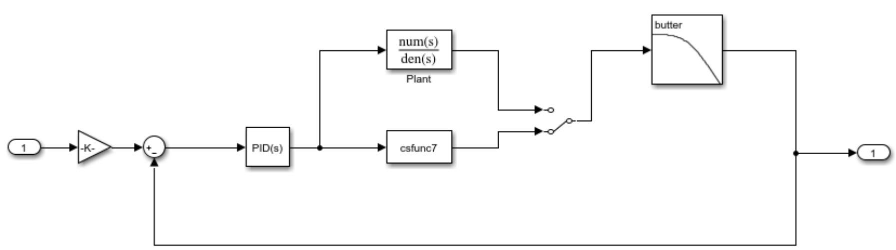


Figure 13: Altered Simulink system design with gain acting on reference signal.

Gain was explored as a method of weighing the reference and output signals differently in computing the error signal. As seen in Figure 14, using proportion-only control with a gain block on the input signal, it is possible to obtain an output that converges to the reference signal and meets the steady-state error targets. Note that due to output noise, the passband edge frequency had to be reduced to 0.6 rad/s in order to meet the steady-state error target. These plots were taken for $P = 0.002055$ and $K = -100$, which were found to correctly steer the output to the reference signal. Altering either of these figures would move the steady state outside of the desired range, marked by the reference lines at 0.98 and 1.02. Furthermore, while this system exhibits significant undershoot, it was found to have no overshoot. The rise time was found to be 34.2 seconds, and for $\epsilon = 0.02$, the settling time is 45.2 seconds. As the output remains within ϵ of the reference signal from this point onward, it is verified that this system design meets all of the required targets.

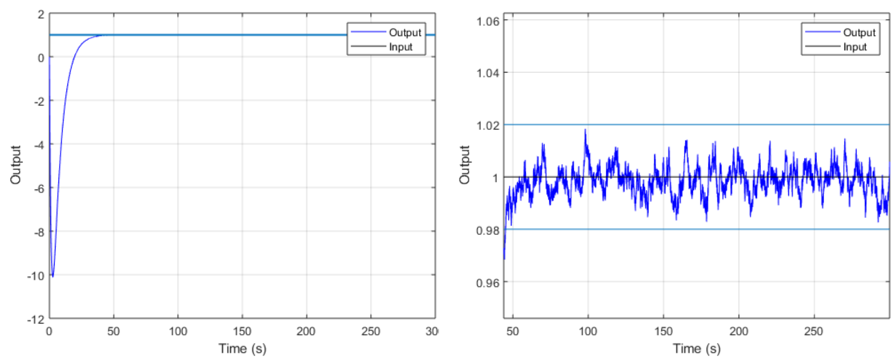


Figure 14: Step response of altered system meeting all design criteria.

Step response parameter	Target value	Actual response
Steady-state error	0.02	0.02
Rise time (s)	38	34.2
Overshoot	0.4	0
Settling time (s)	57	45.2
Settling time (ϵ)	0.02	0.02

6.2 Stability analysis

We want to ensure that our modelled dynamics (open loop transfer function) as well as the closed loop feedback system in Figure 13 are stable. This is because it is unacceptable for a system to produce an output that either explodes or does not converge to the reference signal for the purpose of this project. Also, for potential application areas, it is desirable to have that a system will generate a bounded output response for a bounded reference signal.

The types of stability considered are BIBO stability for the modelled dynamics alone and IBIBO stability for the closed loop feedback system involving the PID controller. This is because the internal details (state properties) of the black box are completely unknown, thus we're only concerned about the stability of the input/output behavior of the system.

The BIBO stability of the modelled dynamics was determined by studying 1) the location of the poles of the open-loop transfer function and 2) the impulse response of the transfer function.

Recall that the open loop transfer function is

$$T(s) = \frac{935406(s-0.01)(s+60)}{(s+0.2)(s+30)^2(s+700)}$$

and clearly, all the poles are located in the left half complex plane, which suggests that the modelled dynamics is BIBO stable. To confirm, consider the following:

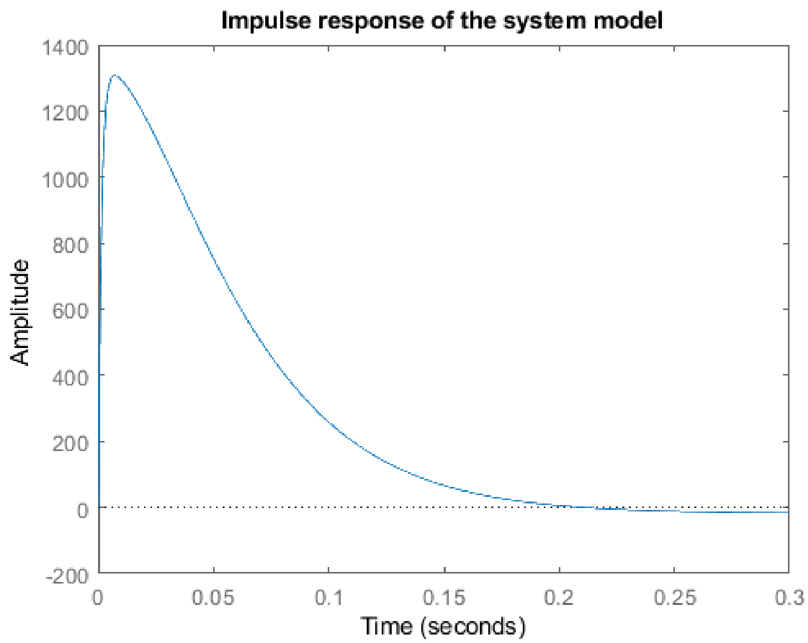


Figure 15: Impulse response of the modelled dynamics

Clearly, the impulse response shown in Figure 15 converges to 0 as time elapses to infinity, showing that the modelled dynamics is indeed BIBO stable.

Furthermore, the IBIBO stability of the closed loop feedback system was determined by studying 1) location of the poles of the closed-loop transfer function and 2) the Nyquist plot for the open loop transfer function.

For a proportional controller with $P = 0.002055$, the closed-loop transfer function is given by

$$T_{CL} = \frac{1922.3(s-0.01)(s+0.2)(s+30)^2(s+60)(s+700)}{(s+0.2)(s+0.1673)(s+30)^2(s+697.2)(s+700)(s^2+62.78s+1070)}$$

Note that this function has no poles in the complex right-hand plane, as the quadratic in the denominator factors into

$$(s^2 + 62.78s + 1070) = (s + 31.39 + 9.20i)(s + 31.39 - 9.20i)$$

Additionally, since the controller is a proportional-only controller, there will be no pole/zero cancellation between T_P and T_C. Therefore, to achieve IBIBO stability, it must be verified that the transfer function's Nyquist plot does not encircle the point at $-1 + 0i$.

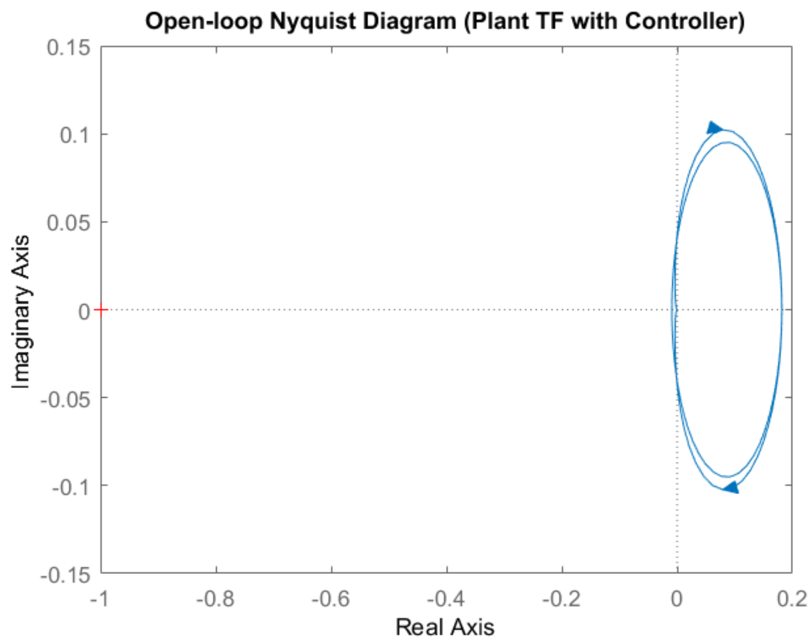


Figure 16: Nyquist plot of transfer function for open-loop interconnected black box and controller system.

Figure 16 shows that the Nyquist plot encircles $-1 + 0i$ zero times, which implies IBIBO stability of the closed-loop system. Since the gain block only acts on the reference input, it will not affect the location of the zeros or poles of the transfer function; it only serves to alter the input as seen by the system. Analysis of the gain margin shows that the system will remain stable for values of P up to 0.2245. However, as previously noted, altering P causes a change in the system's steady state endpoint, causing the system to deviate from its targets.

6.3 Conclusion

In conclusion, choosing the proportional-only control of P = 0.002055 with a gain of -100 added to the input signal ensures that the controller will successfully steer our black box system to the prescribed targets while ensuring IBIBO stability of the closed-loop feedback system. Moving forward, if one wishes to make the modelled dynamics of the black box system more stable, addition of a zero to the transfer function may be considered. In particular, adding a zero in the right half complex plane will increase gain margin positively and reduce the oscillatory motion in the output response, making it more stable [7].

7 Applications Analysis

7.1 Overview

Advancements in the field of robotics have enabled the advent of robot assisted surgery. Recently this industry has experienced exponential growth; over 650,000 of these operations were performed in 2015 [9]. Their popularity stems from their facilitation of minimally-invasive surgery. Typically, these surgeries are less painful, leave less scarring, carry a lower risk of complications such as infections and generally have faster recovery times in comparison to traditional open surgery [11]. A robotically-assisted surgery (RAS) device allows doctors to perform surgeries on patients through computer/mechanical inputs rather than operating the surgical tools by hand. An example of a robotic surgical system can be seen in Figure 17 where each robotic arm can wield a multitude of tools for different surgical tasks.

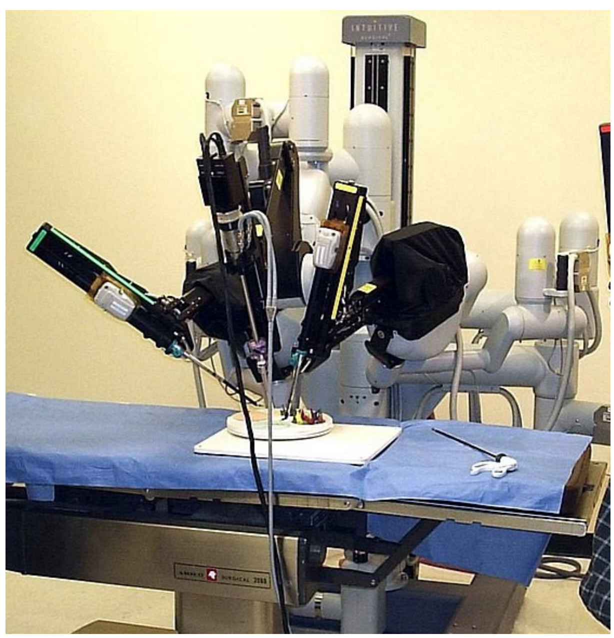


Figure 17: Robotic surgical system not in operation [10].

Although minimally-invasive surgeries can be performed by hand, a process known as laparoscopy, a robotic system can offer added benefits such as performing these surgeries remotely or autonomously. The goal for this project is to design controller specifications for a RAS device such that input commands from the doctor will produce desired operations by the robotic surgical system. The ideal controller must be able to account for prior unknown conditions such as software/mechanical delays and a patient's tissue composition. On top of this the controller must consider the impact on stakeholders in US market and work to meet their needs. The system needs to be economically viable and follow all current surgical codes and standards.

7.2 Codes & Standards Considerations

In the United States, all medical devices must receive approval from the Food and Drug Administration (FDA) before being used on patients. In 2000, the FDA allowed for RAS devices to be used as an alternative for all laparoscopic surgeries [6]. Through research, scientists have discovered that these robotic devices have the ability to perform new types of surgery for the purposes of cancer prevention and treatment. However, not all of these cancer related surgeries have been cleared for operation. Surgeries that are cleared by the FDA are done so based on a 30-day patient follow up. This short term analysis leaves many in the scientific community concerned about the long term effect of these surgeries. The FDA has committed to working with other medical organizations such as The IDEAL Collaboration to continue to research the safety of using RAS devices for cancer related surgeries [8].

Although the FDA determines whether or not a surgical device can be used for operation, they have almost no input on the regulation of training for surgeons to use these devices. This responsibility lies with manufacturers, physicians, and health care facilities and is not overseen by any one group [6]. Third party professional societies have developed programs for the training and certification to operate RAS devices, however, hospitals are under no obligation to use them. If anything were to go wrong while operating a robotic medical system, the medical facility and manufacturers are the ones who can be held legally liable.

The key point here is that as it stands now, there is very little regulation for RAS devices. In the future, as more research into these systems is completed, these regulations could become more stringent. Therefore, the controller for the RAS device must be flexible in order to meet changing specifications. As such, implementation of software updates or manufacturing adjustments needed should be completed with ease.

7.3 Triple Bottom Line

Designing a robotic surgical arm involves the consideration of numerous stakeholder perspectives. These stakeholders include patients, hospitals, surgeons, manufacturers, and the education system. Consideration of these various perspectives will help influence the design of this product to ensure satisfaction from all stakeholders.

Doctors:

One of the most prominent stakeholders to consider is the doctors and medical professionals who will be operating the RAS device. A robotic surgical system is a complicated machine that requires a substantial amount of training to operate efficiently. RAS devices are known to have a steep learning curve which causes surgery time to increase drastically during its initial use in the hospital. The training process requires that the entire surgical team be present since the team is required to understand the robot's functionality as well as being comfortable working in the space around it. Becoming proficient with each of the robot's operations takes surgeons approximately 8 attempts [8]. With there being hundreds of operations that the robot can perform, the training time can be lengthy. As training becomes more regulated, doctors may be required to prove machine operation competency every few years to ensure operational intelligence. Learning to operate a RAS device does have benefits which include allowing doctors to sit while performing a surgery, reducing exhaustion during surgery. This simple benefit can lead to less job stress and create a more comfortable work environment. Another financial consideration is the potential increase in medical school cost if colleges opt to purchase an RAS device for its students. Doing so could lead to increased student debt due to higher schooling costs. The best way to mitigate the learning curve is to design a user friendly interface so surgeons can easily adjust to using the system. The system delay should be minimized for the surgeon so that their control over the robot feels natural and smooth. The easier the RAS device is to understand, the less time doctors will spend training to use it.

Patients:

When a robotically-assisted surgical device is available at a medical facility, patients are given an option as to whether they would like the device to be used during their surgery. Surgeries performed with RAS devices are more expensive, with an average cost of $23,646 [8]. While this is more expensive than an open surgery these is less risk associated to these types of procedures when compared to open surgery. On top of that, when compared to laparoscopy, the only difference is in terms of upfront costs, with the average robot assisted surgery costing around $3000 more [8]. Patients who undergo this style of surgery are required to give consent to the doctor performing the operation and must acknowledge the risk of a robot malfunction. Meaning that if a complication were to arise during the surgery due to a computer error, a patient's life could be drastically affected with little to no option for compensation. There are benefits of robot assisted surgeries especially when it comes to their use in specialized procedures. The process of removing the prostate gland, known as prostatectomy, has shown much higher levels of satisfaction from patients who opted for a robotic-assisted surgery [8]. The recovery rate of these patients is around 25% better than when compared to those who underwent laparoscopy. Another key benefit of using RAS devices is the ability for surgeons to perform surgeries remotely, either from another city or another continent. Many surgical procedures require experts from their respective field. Rather than forcing a patient to travel, RAS devices allow these surgeries to be performed with ease. Although remote surgeries like this have been performed, the delay between the control end and the operating end increases significantly which can hinder a surgeon's efficiency [13].

Because of these considerations, the controller for our RAS device must have an advanced telecommunication system for feedback data related to communication delay. The controller should also be as accurate as possible to compete with existing robotic and laparoscopic surgical options. The system should also have an almost 0% chance of failure. These requirements mean that the steady state error for the controller should be as small as possible.

Hospital Owners:
Institutions where RAS devices are used hold a great deal of responsibility to ensure the doctors operating the devices are appropriately trained. The doctors must also understand all the advantages and disadvantages of the system. If patients feel that they have been misinformed or suspect a lack of experience from a doctor who performs robot-assisted surgeries, the hospital could be held legally liable. The process for surgeons and their team to become fully trained typically costs $10,000 [12]. Not only do hospitals have to spend money to train the team, they also lose doctors during the training process. The equipment itself is not cheap either with a cost of approximately $2 million for the average RAS device [12]. The equipment requires maintenance after every 10 surgeries costing the hospital between $3500 per surgery to replace used parts [10]. An important note is that the waste produced from RAS devices is very similar to the typical waste produced by hospitals. At the end of the machine life time, the system is disassembled and decommissioned by the manufacturing company. This waste does have an environmental impact. In 2006, it was determined that robotic-assisted surgery directly resulted in 303 tonnes of carbon dioxide emissions [14]. An upside to hospitals owning a RAS device is that it conveys a sense of technical superiority in comparison to other hospitals. Robotic-assisted surgical devices are advanced pieces of technology and therefore attract attention from the general public. The systems could be used for marketing means to increase business and attract new patients [17].

The RAS system being designed must conform to similar specifications as RAS devices on the market today. Any major design modifications must take into account that hospitals do not want a new type of waste to dispose of. Any updates required for the system controller should have no impact on the daily work being done at the hospital.

Education System:
As RAS devices become more widely used, educational institutions could begin to implement them into their medical studies programs. This implementation would allow medical students to gain experience operating the devices before entering the workforce. This transition would be a major adjustment for the

school and comes with many drawbacks that have been previously mentioned. Instructors would be required to train on RAS devices in order to aid students in their studies. On top of that once implemented in the program, RAS device training could result in an increase of class hours leading to more work and higher stress level of students. Educational institutions need to ensure this is not the case so as to not discourage young students from applying to medical school. If the school were to purchase a machine of their own, the costs of installation and maintenance costs would be similar to those of hospitals. Again, similarly to hospitals these devices are a great way for a school to market itself as a leading institution and can create an increase in student satisfaction.

Designing the robot system to be fully operational for training purposes is required. Allowing for students to train on the robot without wasting medical supplies would be an economic benefit for educational institutions and would reduce the disposal of waste.

Manufacturers:
Finally, the manufacturers producing the robot surgical systems have a great deal to gain and lose from the device's design. In 2016 surgical robotics was valued in the global market at approximately $5.7 billion. By 2023, this number is expected to reach $24.4 billion due to a forecast increase of 23.6% per year [15]. However, to become a player in this market, a manufacturing company needs to stay competitive. Doing so means designing an efficient production process to keep costs low. Most of the company's profit should be put towards R&D advancements in order to continue to improve the robot's system and the controller used with in it. Another important consideration is the use of raw materials and the CO_2 emissions associated with the production process. Although very little information is available on this topic, it is clear that the manufacturing process negatively affects climate change. Simply using less raw materials is not always a viable solution to combat environmental issues as it can result in a less effective product [16]. At the end of the day manufacturers are responsible for the functionality of the robotic-assisted surgical device and if anything were to go wrong during operation, eyes would turn toward them. Therefore, an accurate and efficient product with minimal error is the best way for the company to avoid negative publicity and maintain a strong market standing.

Due to the level of complexity and accuracy needed for the design and manufacturing process, experienced engineers and doctors will be needed if the company wants a finished product in a reasonable time. This would result in high initial costs but is necessary for the company to thrive in the long run. A strong engineering team would save the company costs related to manufacturing efficiency and minimal use of raw materials. Finally, it is of the utmost importance that manufacturers develop the technology to near perfect standards and ensure that it is rigorously tested before being sold in the market. To stand out, it needs to be technologically competitive with current minimally invasive techniques such as laparoscopy and existing RAS devices.

7.4 Economic Analysis

Designing a new robotic surgical system requires a significant focus on the economic costs and benefits relating to this design. First and foremost an analysis of the American robotic surgical market must be conducted in order to determine the viability of the product. A financial strategy for the system must then be developed with a focus on research and development costs as well as pricing for the unit. An overarching economic analysis must also be conducted to determine the impact of such a system on the economy as a whole. These factors will influence design specifications and the pricing strategy of the system.

Currently, the market for robotic surgical systems is dominated by Intuitive Surgical Inc [17]. This company is the designer of the da Vinci System which is the leading robotic surgical system in the world [17]. Intuitive Surgical is a multibillion dollar company with just over \$3.7 billion in revenue in 2018 [24], and achieved a growth of 19% that year. These facts show that there is a large market for these surgical systems and that the market is still growing at a significant rate. Intuitive currently sells the da Vinci system for over \$2 million (USD) with specific pricing dependent on the hospital purchasing the system [19]. In addition to this initial cost there are yearly maintenance costs, approximately \$185,000, and an average cost per procedure of \$3,500 [19]. A large portion of this procedural cost is the result of Intuitive Surgical requiring that the surgical tools at the end of the robotic arms be replaced after every ten procedures. However, there is no clinical basis for such a limitation on their surgical tools. [18] Clearly, a market of this size could benefit from competition to reduce the high consumer costs [21]. Entering the market however, will require a strategy designed to reduce the dominance of Intuitive Surgical.

In order to gain any traction within the robotic surgical market the product being designed must be differentiated from the da Vinci System. The goal will be to create a product of similar or better technical quality that has a lower per procedure cost than the da Vinci system. To begin design and creation of such a product, a significant sum of funding must be secured. This funding will be necessary to research and develop the product as well as to market the system to hospitals in the US and to begin the process of seeking FDA approval. Based on the initial funding received by Intuitive Surgical, the necessary initial funding for such a venture is approximately \$75 million [24]. This funding would be structured in tranches with \$10 million initially and with follow on investments of \$20, \$20, and \$25 million, respectively. Funding of this magnitude is reasonable given the size of the market and the need for competition within it. In order for the company to continue to grow beyond this initial stage, either an IPO (given that the product would be proven at that point and initial investors would be looking for an exit) or additional private equity funding with a value of approximately \$60 million would be required. Assuming that funding is secured for the development of the system, the system will be priced at approximately \$1.5 million. This price point is chosen with the goal of undercutting the cost of the da Vinci system and gaining a portion of the market share. It is also a price where a profit of approximately \$900,000 would be earned on each sale of the system [23]. The price of the system will also be reduced for teaching hospitals in hopes to encourage students learning at those hospitals to train and become comfortable using the system. The goal of this strategy is that doctors trained on the system will request that a RAS device be put in place at hospitals they work at in the future which will increase the demand. The price of the system in this case will vary between hospitals and is dependent on the number of fellows that the hospital would be training. The training of more fellows would result in a further reduction of the price of the system. Additionally, an analysis on the wear of surgical tools will be conducted with the hope that the tools can be reused for more than ten surgeries through improved component durability. This increase in durability, if possible, would lower the per procedure cost of the system as compared to the da Vinci, thereby increasing its appeal to consumers. Using the aforementioned financial strategy entrance into this monopolistic market is feasible. Upon market entry, numerous benefits to patients, hospitals, and the economy as a whole will be realized.

In order to justify an expenditure of this magnitude, economic benefits must be seen from a number of relevant parties. Some of the benefits achieved relate to a reduction in hospital stay duration for patients who undergo robotic surgery as compared to open surgery. The reduced stay duration is the result of robotic surgeries being minimally invasive, meaning that recovery times are faster and that there is a reduced risk of post-operative complications such as infection [21]. Patients clearly benefit from this as they spend much less time in the hospital. In the U.S. every day not spent in the hospital saves the patient $5,220 [20]. The economy as a whole would benefit as missed days of work result in a loss $3,600 per year for an hourly worker and $2,650 every year for employees with a salary [22]. In the United States hospitals would also benefit economically as there is high demand for this technology among patients [17]. This demand means that ownership of this product would result in more patients attending that hospital, increasing hospital revenue. As compared to the da Vinci equipment, hospitals would also experience a lower initial cost and a reduced per procedure cost which would increase the profit of these operations. While robotic surgeries may cost more than traditional open surgeries, these benefits outweigh that cost making the design of this system worth pursuing.

7.5 Concluding Remarks

Designing a robot assisted surgical system requires the consideration of numerous stakeholders and economic factors. Analyzing these considerations led to the development of design criteria that the system must meet. These criteria fall under operation and cost of the system and ease of training on the system.

Performing surgery is a strenuous job that requires a high degree of precision and accuracy in order to ensure patient safety. As such, a robotic surgical system will need to maintain a high degree of spatial accuracy while being comfortable for the surgeon to use. In general, there is a trade-off between speed and accuracy, however, a robotic surgical system requires both. While there are no standards for the precision requirements of a robotic surgical system, the surgical arms would need to mimic the surgeons hand motions exactly [25]. This requirement ensures that surgeons have absolute control over how the surgical arms are interacting with the patient, reducing the risk of complications. Given a mechanical input, the system should also incorporate some form of tremor reduction so that unwanted movements in the surgeon's hands are not translated to the patient [25]. On the other hand, the system should also translate the movements of the surgeon's hand in real time in order to reduce time spent in the operating room. Less operating room time leads to a lower cost for the surgical procedure and the ability to perform more operations in a given period of time. The controller should then take the current spatial position of the robotic arm and the hand movements of the surgeon as inputs. Using these inputs, the controller should move the arm to the correct position in space. Both of these factors work to reduce the cost of surgery for patients and hospitals. Additionally, the system should be designed with comfort of the surgeon in mind. Doing so requires that surgeons of various body types be able to sit comfortably in the system for hours at a time. As such, the system will need to have an element of adjustability so that persons of differing stature will be comfortable using it. The system will also need to be reliable and durable so that it can be used for years after it is purchased. This durability also comes into play during the short term so that surgical tools do not have to be replaced after every ten uses. Increasing the time until replacement of these tools reduces the cost per surgical procedure of the system, which benefits both patients and hospitals. Ensuring that the system is operationally sound and is relatively inexpensive will lead to success in entering the robot assisted surgery market.

Transitioning between traditional open surgery or laparoscopic surgery and robotic assisted surgery is a time consuming process that impacts surgeons, hospitals and most of all, patients. In order to make this transition as smooth as possible for surgeons, the system should be designed such that it mimics open and laparoscopic surgeries as closely as possible. Currently, one of the largest gaps between robotic and open surgeries is that surgeons are unable to tell if they are touching tissue when using a robotic system. To remedy this problem, the controls of the system should incorporate haptic feedback in the form of vibrations so that the surgeon can "feel" what the robotic surgical arm is touching. Additionally, the system should have an included virtual reality training program for a wide variety of surgeries. A training program such as this would allow surgeons to quickly gain experience with the system without any risk of patient complications. This program would also increase the speed with which a surgeon could become operation ready because it would allow them to practice in their spare time, rather than relying solely on patient availability. A smooth transition such as this also appeals to hospitals since surgeons would be ready to use the system quickly, allowing more surgeries using the system to be performed from the time of purchase.

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