Thesis Project Portfolio

Design and Control of a Rotary Inverted Pendulum

(Technical Report)

The Effects of Automation and Robotic Presence on Unemployment and the Economic Health of Workers Both on a Large Scale and Individual Basis

(STS Research Paper)

An Undergraduate Thesis

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

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Executive Summary

The robotic revolution has shaped the world we live in in ways that mere decades ago were though impossible. Today mankind has created mechanical systems that have revolutionized manufacturing, warfare, medicine, and so much more. These impressive mechanical systems are a critical part of our growing society, and are only growing to become more present within our society from day to day. The capabilities of these systems, both good and bad, are why I have chosen the capstone topics that I have. My technical research is in the design and control of a rotary inverted pendulum (RIP). I chose this topic mainly due to my interest in control theory, but also at the request of Professor Michael Momot. Prof. Momot wanted a system he could use as a teaching aide in his undergraduate sections of controls. My STS research topic is the the effects of automation and robotic presence on unemployment and the economic health of workers both on a large scale and individual basis. I chose this topic in order to foster a deeper understanding of some of the effects of robotic systems as they are integrated into society. I wanted to determine if the semi-common fear of robots ruining the job economy for their human counterparts was based in reality or simply a ruse. The fundamental design tools and principles used within the design of the rotary inverted pendulum mechanical system are also the same tools that industry altering robotic systems are built off of. In this way, the principles I exercised in the design of the rotary inverted pendulum are of the same vein as those used in these industry staple robotic systems that could potentially harm human employability.

Prof. Momot's idea for a teaching aide was a variable gain rotary inverted pendulum as it is a classic example of control theory and is widely used to test different controllers and control schemes. To this end, he wanted us to create a rotary inverted pendulum system that could have its system parameters and controller algorithm altered on the fly, such that he could show his future students in real time what effects each parameter have on the output procedure of the system. Prof. Momot believed a real world demonstration of the control concepts present in the RIP would hugely benefit the learning and understanding of his students. To do this, we utilized our prospective system equations of motion to create a usable plant to dictate how we needed to drive the system from moment to moment. In order to modify the system and account for real world error, a PD controller was also created for use within the system that would modify the way that the system was driven such that we could fine tune the specific results of our system and achieve the most desired outputs for our application as an aesthetically pleasing teachine aide.

The capstone project was overall a success. The pendulum system works well enough as intended such that Prof. Momot will be able to use it as is for an aide, but he will also likely be doing more work on it with future graduating engineers such that the system can be made even better. Only a select few system parameters and controller parameters cannot be altered on the fly, with the majority of these being highly non-influential. The system will work well as a teaching aide as is at the moment, but it also has high potential to be modified in the future such that Professor Momot can achieve all of the desired characteristics within the system.

For my STS research topic I decided to see if I could find a relationship between the introduction of these systems into industries and the overall health of the national economy as well as the health of individual workers at different levels of employment within these affected companies. I wanted to undergo this research such that I could be sure that my desired future projects within the robotics industry would be beneficial to all parties, or at least detreimental to none. My methodologies involved looking at various statistics for economic health and personal income across various time periods of United States history. I adjusted the monetary values for inflation rates and then compared these wages and GDP amounts from periods of relatively little robotic presence within the workforce to periods where there were high rates of robotic presence. Most of the anslysis that was done was simple calculated net changes and average rates of change by virtue of these statistics being very conclusive on their own.

In the end, the data suggests that automation and increasing robotics presence within the workforce hugely benefits corporations and their upper echelon of CEOs and executive workers and the overall productivity of the United States as a whole. Wages of these executive workers and board members have skyrocketed as more and more robots have been added to the workforce, and the United States GDP has grown to new heights. On the other hand, workers whose jobs have the potential to be replaced by these systems saw their wages actually decrease. Even the average, middle class worker would only be making less than a dollar more than they would have 4 decades ago, when upper class wages have increased by 150% within the same industry. I cannot conclusively say that this suggests that robots are bad for the economic wellbeing of workers in their industry, as the economy and wages as a whole are incredibly volatile and difficult to fully define their causes and effects. However, I am confident that there will need to be an increase in policy and laws surrounding robotic systems being implemented within the workforce in order to protect workers and their wages. It would appear that robots in the workforce asymmetrically benefit higher earners much more than lower earners whose jobs could be replaced by the machinery, but further research would need to be done to determine if this is an issue inherent to robots in the workforce, or rather if this is a systemic issue caused by corporate America.

Capstone Design Project

(MAE 4610)

Design and Control of a Rotary Inverted Pendulum

Design Team Advisor:

Professor Michael Momot

Group Members:

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Fall 2023

Introduction

The goal of this capstone was to design and develop a functional rotary inverted pendulum (RIP) for use as a teaching aide by Professor Michael Momot when teaching control theory to UVA undergraduates. A rotary inverted pendulum is a classical example of control engineering often used to study and demonstrate differing control strategies. In a RIP system, typically a pendulum arm is attached to a pivot point that can rotate 360 degrees by some motor or actuator. A fully developed RIP should be able to fully control the motion of the pendulum arm by precisely driving the arm which the pendulum pivots about. The goal is to swing the pendulum arm up and balance it vertically in the air using rotational motion. The dynamics of a rotary inverted pendulum include both translational and rotational motion, and as such the control system needs to consider the angular position, velocity, and acceleration of the pendulum, in addition to its linear position and velocity.

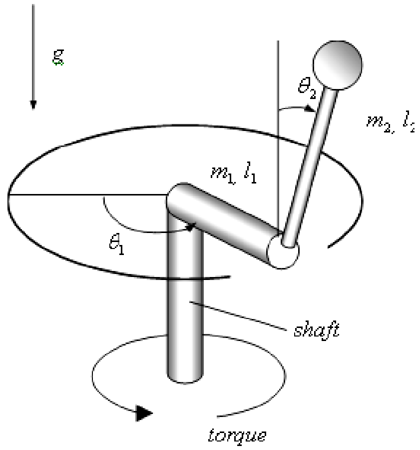


Fig 1: RIP Diagram

The RIP was designed with several constraints given by Prof. Momot: The RIP needed to be lightweight, portable, and aesthetically pleasing so it could be used in classroom demonstrations by Professor Momot. Specifically, the maximum weight of the RIP was given as 16 pounds, and it should be no more than 1 foot tall. Additionally, the volume of the RIP should remain under 1 cubic foot. These constraints ensure that the RIP can be easily carried from room to room, and set up quickly and with minimal space necessary. The RIP must be designed to be easily disassembled, so parts could be swapped out in the event of wear and tear. In order to be of use within classroom demonstrations of system variation within control systems, the weight of the pendulum arm should be easily moved across the arm. During use, the RIP should have minimal vibrations, i.e. not move along the surface it is placed upon or move a small table. It should also be able to attain an inverted state and hold it within 1 degree of equilibrium for a minimum of 10 seconds. Parameter gains K_P , K_D , and K_I should be easily changed through the microcontroller, ideally during use.

Technical Calculations

The full derivation of the system equations of motion and complementary forces and torques present within the rotary inverted pendulum can be found within Appendix C and Appendix D respectively. The resulting equations of motion, solved for by utilizing the Euler LaGrange equation of motion on both the rotary arm and pendulum arm are respectively are as follows:

$$\frac{d^2\theta_1}{dt^2}(J_1 + m_2 l_1^2) + m_2 l_1 l_2 (\frac{d^2\theta_2}{dt^2} - (\frac{d\theta_2}{dt})^2 \cdot \theta_2) = T_{in} \quad (1)$$

$$m_2 l_2 (l_1 \frac{d^2\theta_1}{dt^2} - g\theta_2) + \frac{d^2\theta_2}{dt^2}(J_2 + m_2 l_2^2) = 0 \quad (2)$$

Both equations were linearized by making the assumption that for small angles (less than 30 degrees) sin(θ) is approximately θ, and cos(θ) is approximately 1. In equations 1 and 2 any variable with subscript 1 refers to the rotary arm, and any value with subscript 2 refers to the pendulum arm. J refers to the arm's mass moment of inertia about the arm's center of mass. θ refers to the angle of the arm relative to some determined zero. M refers to the arm's mass. $l_1$is the distance along the rotary arm longitudinal axis between the rotary arm center of mass and the projection of the pendulum arm center of mass onto the longitudinal axis of the rotary arm. l_2 is the distance from the pendulum arm center of mass to the longitudinal axis of the rotary arm. The gravitational constant is g in the above. T_{in} represents the input torque to the rotary arm. These equations of motion are what will ideally be used alongside a state space representation of the system to create a precise controller.

As a brief cautionary check, we determined what forces and moments we could expect our machinery pieces to undergo. The full derivation for these values can be found in Appendix D, but the maximum values were found to be characterized by the following:

$$m_2(-\left|(\frac{d\theta_1}{dt})^2 \cdot l_1\right| i + \left|(\frac{d\theta_2}{dt})^2 \cdot l_2 + g\right| j - (\frac{d^2\theta_1}{dt^2} \cdot l_1 + \frac{d^2\theta_2}{dt^2} \cdot l_2)k) \tag{3}$$

It is important to note here that the directional unit vectors are somewhat arbitrary here as these magnitudes will remain constant for constant velocities and accelerations, just in varying directions. Using expected velocity and acceleration values for our system produced forces well below anything that could deform any of our parts, making further stress calculations unnecessary. Assuming necessary angular acceleration and angular velocity values for both bars of 30 radians per second and 30 radians per second squared respectively, principal stress values barely reached greater than half of the yield strength of our materials affected. Keep in mind that this is the case when substituting in values near 5 revolutions per second, much higher than anything we would need for our system.

Additionally, in order to avoid driving the system near its natural frequency, we needed to determine what said natural frequency would be for our desired design.

$$k = \frac{F_A}{\delta} = \frac{-3EI}{H} \tag{4}$$

$$\omega_n = \sqrt{\frac{k}{m}} \tag{5}$$

Equation 4 was our derived spring constant for the load bearing portion of our frame. E represents the elastic modulus of our load bearing supports, I represents the area moment of inertia for those supports, and H is the distance from the base of the frame that the load is applied to the frame from the mechanical portions driving the system. Equation 5 relates the spring constant k and the mass of material fixed to the frame m to the natural frequency of our system. The full derivation of the results can be found in Appendix E. The first natural frequency of our system based off of the current design is upwards of 47 revolutions per second or 7.5 Hz. We expect to be able to stay well below this threshold when operating our system.

Design and Implementation

Mechanical

The group came up with a plethora of ideas regarding the design of the RIP. We began by researching existing rotary inverted pendulums and noted key features of their design. In order to best organize the ideation process, we have divided it into 3 categories: Frame, Rotation, and Control.

The frame needed to be lightweight but strong, aesthetically pleasing, and stable. The group started with material considerations. Laser cut acrylic was proposed, but rejected because of difficulty in assembly. A metal frame was discussed, with multiple variations put forward. A box made from welded pieces of angle bar, a large machined block, and a custom design made from entirely machined parts were among the designs considered. The group decided that a metal frame would be too heavy to haul between classrooms, difficult to take apart, and the cost and labor involved in making the frame would be too much. We reasoned that the expected forces that the frame would have to withstand would come nowhere close to the magnitudes that would make the strength of a metal frame necessary. 3D printing was briefly considered, but it would severely limit the possible designs of our system, and the size of the pieces required would force us to print in numerous sections. Eventually the group decided to create the frame out of wood. Wood was selected due to its sufficient strength, light weight, aesthetic qualities, and machinability. As a bonus scrap wood was readily available for use within the project.

The main features reviewed relating to function of the RIP were the workings of the inner rotating parts. First, the group debated how the motor should attach to the rotating pendulum arm. The group was in agreement that the motor should connect to a vertical shaft which would then connect to some kind of a horizontal bar housing the pendulum arm. How the motor should connect to the vertical shaft, however, was a point of contention. Three main designs were proposed. First, the motor connects directly to the vertical shaft, and then consequently to the pendulum arm. Second, the motor connects to the vertical shaft through a series of gears. Third, the motor connects to the vertical shaft through a pulley or series of pulleys. The motor directly connected to the driveshaft was the simplest solution, however the rapid accelerations required to precisely control the system required extremely high torques that the base motor was not capable of producing. For this reason, this design was scrapped.

Utilizing gears within the system had a few key drawbacks that prevented the group from moving forward with it. Gears are subject to backlash, which could have added uncertainty and limited the precision of collected rotation measurements that needed to be very precise. Finally, for the ratios we desired, gears would need to be machined, adding to the overall cost and complexity of the production process.

The group ended up settling on a pulley drive system with a 1:3 gear ratio. Using a pulley would solve the problem of the motor not having enough torque. Additionally, with proper belt tensioning, the pulleys were expected to give minimal deflection or slippage

The control of the RIP refers to the parts involved in reading the position of the pendulum arm, the microcontroller, and the equations of motion and software used to direct the motor. A rotary encoder was decided upon as the best means for detecting the positions of the pendulum arm and rotary arm. A multi-turn encoder was necessary because the pendulum shaft needed the ability to rotate 360 degrees in either direction. The resolution of the encoder needed to be quite high, so the system could adjust quickly to small changes in position. The final system made use of two separate quadrature encoders. One of these encoders was directly attached to the swinging pendulum arm that collected the angle of the pendulum arm relative to the vertical position and another attached to the base of the motor to measure the angle of the rotary arm relative to some designated zero.

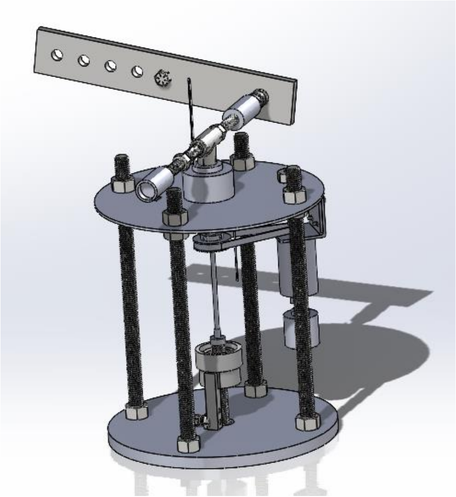


Fig. 2: First Rough Assembly

This design choice demanded that a slip ring be included, as the encoder directly connected to the pendulum arm would have to have the ability to rotate 360 degrees without any wires wrapping around the vertical rotating shaft. A slip ring with a hole through the middle was chosen so that it could be placed directly onto the vertical rotating shaft, minimizing the amount of contact the slip ring had with the moving assembly and ensuring it wouldn't be placed under any loads.

The entirety of the 3D modeling was performed in SolidWorks. In order to streamline the process of designing and ordering parts, the group used as many stock pieces such as nuts and bolts from the McMaster catalog as possible. Our design went through several iterations during the design process, and even more iterations during final assembly. The first full assembly is shown in Fig. 2. This design consists of a cylindrical frame, held together by 4, ⅝" steel bolts. The motor is mounted to the top of the frame, along with an encoder mounted by a custom designed rotary coupling under it. A pulley is attached to the motor, which drives the central rotating shaft. A taper bearing in a custom designed holder can be seen at the bottom, and attached to that shaft on top is a slip ring and the bar that connects to the pendulum arm. The inclusion of the taper bearing was to ensure the central rotating shaft could not jump upwards as the pendulum spun. The pendulum arm features a bolt on its end that can be switched between several holes and acts as a weight that could be used to vary the position of the pendulum arm's center of mass. There is a bearing press fit into it which allows it to rotate around the horizontal bar. After convening and discussing this design, the group decided to improve on a few key features.

First, the slip ring on top of the frame was supporting the weight of the pendulum arm. It was decided that it would be best if the slip ring was not in a load bearing position. Secondly there was a need to improve the aesthetics of the design and cover up any potential moving parts that could lead to injury or a malfunction.

This led to the second design iteration, shown in figure 3. In this design, we included a completely revised frame featuring a wooden shroud. This shroud serves a few different purposes. It conceals the inner working of the RIP, acts as support for the 4, ⅝” steel bolts, and is the new mounting point for the motor. A new supportive frame connecting directly to the steel bolts was added to reduce vibrations and increase stability.

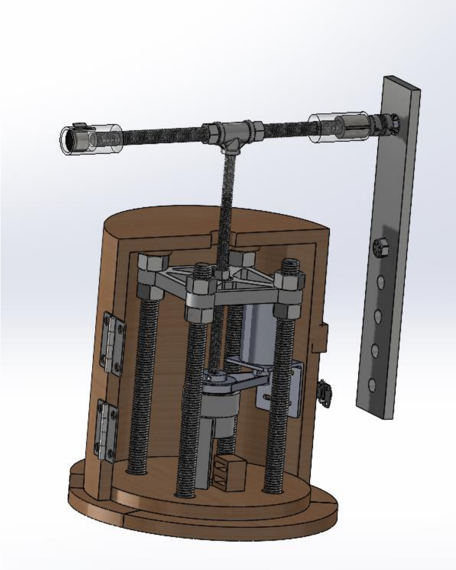


Fig. 3: Second Draft Exposed Assembly

The decision was made to use two encoders, one on the pendulum arm and one on the motor. Additionally, there were concerns regarding the weight and balance of the existing design. Figure 4 shows the fully updated result. A flat rectangular 6061 aluminum beam was used as the rotary arm in order to allow for easier mounting of the encoder and pendulum arm, while the pendulum arm itself was a bent ¼” stainless steel rotary shaft. The aluminum beam was chosen due to its low weight and so it would be easy to attach 3D printed mounting brackets for the encoder and pendulum arm. It mounts to the central, vertical rotating arm by a coupling that will be welded onto the bottom of the beam.

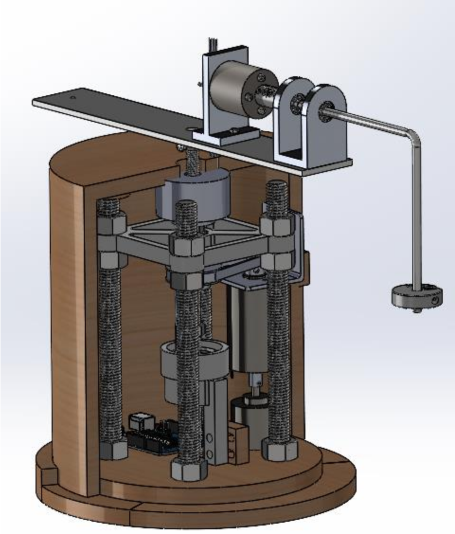


Fig. 4: Updated Full Assembly

The encoder now screws onto a mounting bracket and attaches to the pendulum arm via a coupling. This allowed for easier mounting of the pendulum arm to the encoder as we were not forced to press fit the bearings to the rod to balance the horizontal forces that the pendulum arm motion would create. The pendulum arm itself is supported by 2 ball bearings press fit into a bracket that bolt onto the aluminum beam. On the end of the pendulum arm is a quick release aluminum clamping shaft collar that serves as an adjustable weight. A model of an Arduino was added to visualize the clearances within the assembly.

Upon finalizing the design, the group was comfortable enough to start ordering parts and putting things together. The shroud was expected to take a long time to construct, so the group opted to construct a rough frame and assemble the internals around the 4, ⅝" bolts to test out components and tolerances.

Once the group put the motor and encoder together, we did some preliminary testing and realized a few things. The coupling between the motor and the encoder was not going to work. The group ordered a 6 mm coupling to fit the diameter of the encoder, but did not account for the difference in diameter between that and the 5 mm shaft of the motor. This resulted in intense vibrations during testing of the motor.

Furthermore, the central vertical rotating shaft was smaller than the inner diameter of the taper bearing, meant to reduce its freedom to pitch or roll. As a result, that shaft was tipping over, dramatically affecting the rest of the system. To counteract this, the group added another brace on the inside of the shroud, with a bearing in its center that allows the central shaft to still rotate but prevent as much deviation in the rod from the vertical. This final model can be seen in figure 5.

Upon assembling the mechanical pieces of the RIP, a few changes became necessary. The main driving rod was originally made from aluminum, but to avoid bending in the rod due to high stresses from the belt tensioner, the aluminum rod was swapped for a high strength steel one that had a yield strength four times higher than that of the aluminum rod. Additionally, the initial design idea to simply bend the pendulum arm into a 90 degree angle from a flat rod proved too difficult to accurately achieve. In order to work

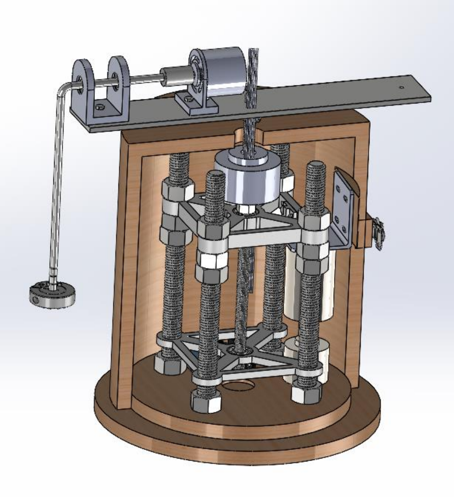


Fig. 5: Final SolidWorks Model

around this, the rod was simply cut to length, then secured within a fixture comprised of two couplings brazed together in a 90 degree angle.

The bill of materials for the final design can be found in Appendix A. Assembly drawings for the final design can also be found within Appendix B.

Electrical

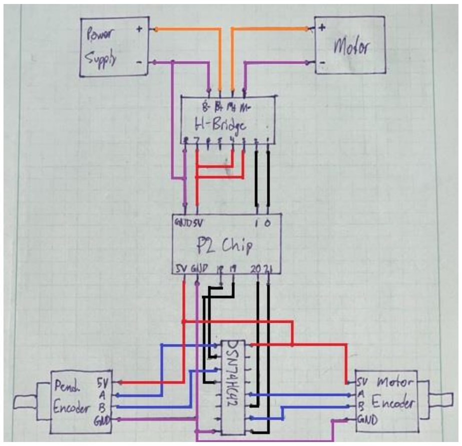


Fig. 6: Circuit Diagram of RIP

The electrical components required for the functioning RIP were as follows. All of the wiring was done through a single breadboard for ease of wiring and so that in the event that the future work done to finalize the system requires a circuit change the change can be made easily and quickly. The direct connections between the slip ring and the pendulum arm quadrature encoder were soldered in order to prevent any noise in the position signals generated from a loose connection between the leads.

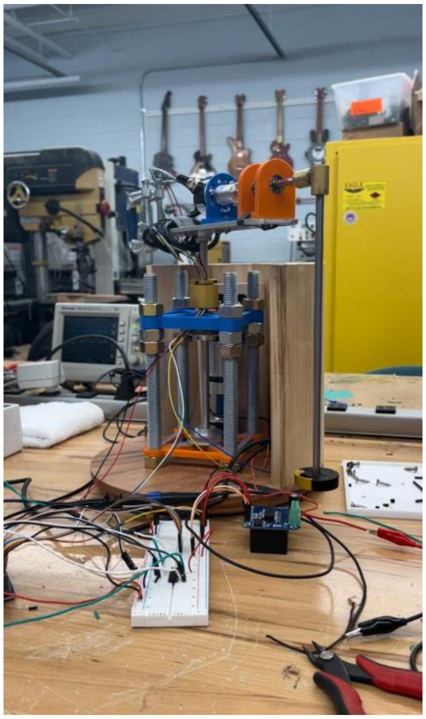


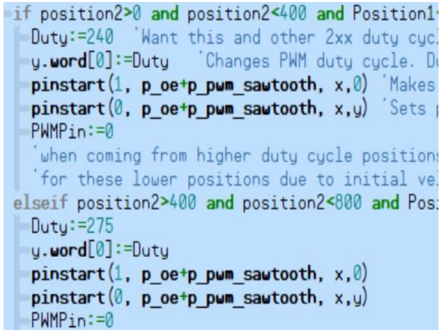
Fig. 7: Final System

In order to precisely drive the motor the BTS7960 motor driver was used. This motor driver module contained pulse width modulation capabilities alongside an H-bridge that allowed the P2 microcontroller to vary the direction of rotation.

Finally, a Schmitt trigger was used in order to clean up the position signals of both encoders. This comparator chip served to remove the majority of noise in the encoder pulses caused as a result of the rising and falling voltages of the encoder pulses giving unclear readouts to the microcontroller as the encoders began rapidly spinning. The circuit diagram can be seen in figure 6, alongside the final completed system with its electrical components exposed in figure 7.

Controls

While testing components of the RIP, a gain scheduling control scheme was utilized to perform basic tests of effectiveness for the system's encoders and motor. While making sure the motor could be driven solely off of the angular position based off of the pendulum encoder, the system proved to be capable of very limited balancing. The pendulum was able to remain within 45 degrees of the vertical position for upwards of 6 seconds. This gain scheduling was quickly made obsolete by attempts at a full PID controller. A snippet of this control algorithm can be seen in figure 8.



```
if position2>0 and position2<400 and Position1
  Duty:=240  'Want this and other 2xx duty cyc
  y.word[0]:=Duty   'Changes PWM duty cycle. D
  pinstart(1, p_oe+p_pwm_sawtooth, x,0) 'Makes
  pinstart(0, p_oe+p_pwm_sawtooth, x,y) 'Sets
  PWMPin:=0
  'when coming from higher duty cycle position
  'for these lower positions due to initial ve
elseif position2>400 and position2<800 and Pos
  Duty:=275
  y.word[0]:=Duty
  pinstart(1, p_oe+p_pwm_sawtooth, x,0)
  pinstart(0, p_oe+p_pwm_sawtooth, x,y)
  PWMPin:=0
```

Fig. 8: Gain Scheduling Controller

Time constraints prevented a proper, detailed PID controller from being created for use in driving the RIP. As a result, the decision was made to simplify the equations of motion. These equations are what will be referred to as the plant of the system from this point onwards. This was done to minimize the time that would be needed for testing quantities on the system such as mass moment of inertia and the unknown motor constants of the used motor.

The plant was simplified from the complicated matrix of two equations that can be seen in Appendix C to a simple model that can be seen in figure 9. This model proved sufficient when properly calibrating the system by repeatedly and slowly shifting the various gains and constants within the system to a point where the system was able to function.

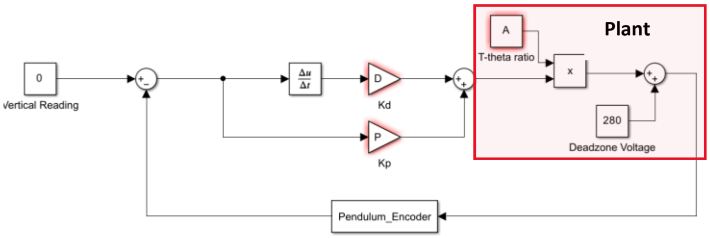


Fig. 9: Simplified Plant PD Controller

Outside of the plant, a simple PD controller was constructed to better drive the RIP system. The optimal proportional gain was found to be just under 15. The optimal derivative gain was found to be just over 1. Implementing this controller with the simplified plant saw success in the functionality of the system with it being able to maintain balance for upwards of a minute before the imprecision of the used plant model became to great for the system to control.

A less simplified model was drafted before the end of the design cycle, but there was no remaining time to implement it and debug the controller. This model saw the originally unknown plant parameters estimated. Specifically, the encoders and attached pendulum mass and counterweights were modeled as point masses to find the mass moment of inertia of the rotary arm by applying parallel axis theorem, while the mass moment of inertia of the pendulum arm was simple enough to calculate by hand.

Results

The RIP designed as a part of this capstone project functions as a good foundation for future students working under Prof. Momot to improve upon and finalize a proper control algorithm. The system met all of the portability requirements. The assembly weighed in at just over 11 pounds, significantly under the maximum given weight of 16 pounds. The total volume of the RIP came out to an overestimated .7 cubic feet, meeting the volume criterion of being under a single cubic foot. More importantly than this, Professor Momot was able to lift and move the RIP around. The vibrations created from the operation of the system were minimized by applying counterweights to the rotary arm, allowing the meeting of the vibration criterion.

The functional criterion of the RIP were mostly met as well. The RIP system is able to maintain its position within 1 degree of the vertical for well over 10 seconds, however the gains are not variable during motion. The nature of the plant model that was utilized prevents extreme changes in the system gains as the current system is imprecise. With proper calibration of the RIP the team was able to create a demo that saw the RIP, when started from the vertical, maintain its upright position for upwards of 5 minutes. However, the dynamics of creating a swing up controller for the RIP were also quite difficult to characterize in the time frame that we had, so the specification to have the RIP be capable of swinging itself up from rest to the vertical position was not met during this design cycle.

Conclusion

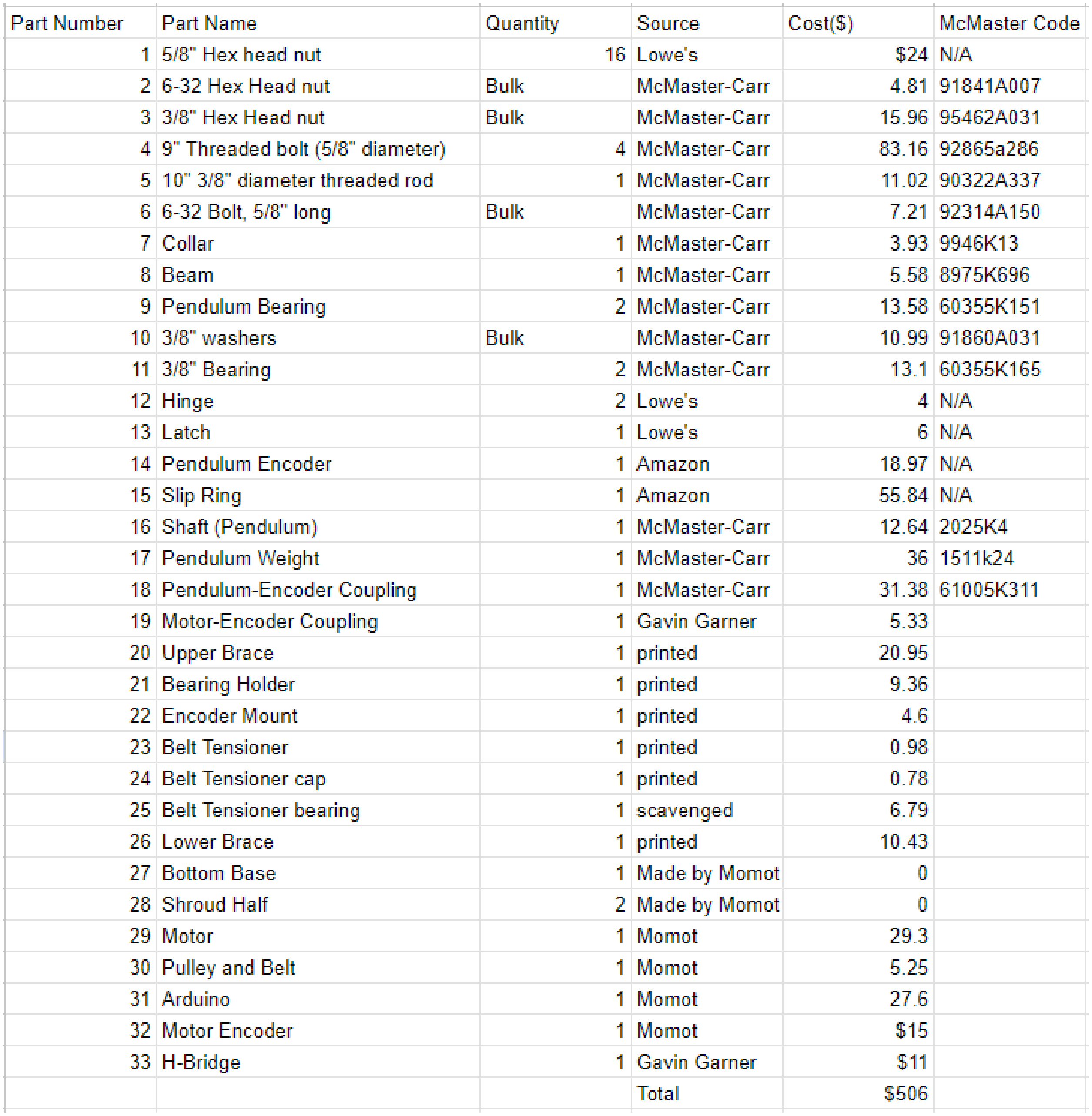
While some of the system capabilities and parameters that were originally desired to be implemented within the RIP system were not implemented, the mechanical construction of the current system was properly done in such a way that future groups working on this project should only have to focus on fine tuning the control algorithm of the system.

The current construction of the RIP is not a finished product, as the machining time required to create some of the semi complicated geometries required limited the amount of time that could be spent fine tuning the controls. With the construction of the system out of the way, the RIP should be capable of being fine tuned on the controls side. In this way, the system is a success as the construction of the RIP was done of such quality that it should be usable for years to come. The easy disassembly should allow easy mathematical and/or experimental determinations of the system parameters that the team was not able to determine for lack of time and a solid experimental plan.

Given another year of design and engineering work from a similar sized team of engineers, we fully expect that the RIP could be upgraded such that it meets all of the criteria originally set forth by Professor Momot and becomes a fully finished, precisely driven mechanical RIP system.

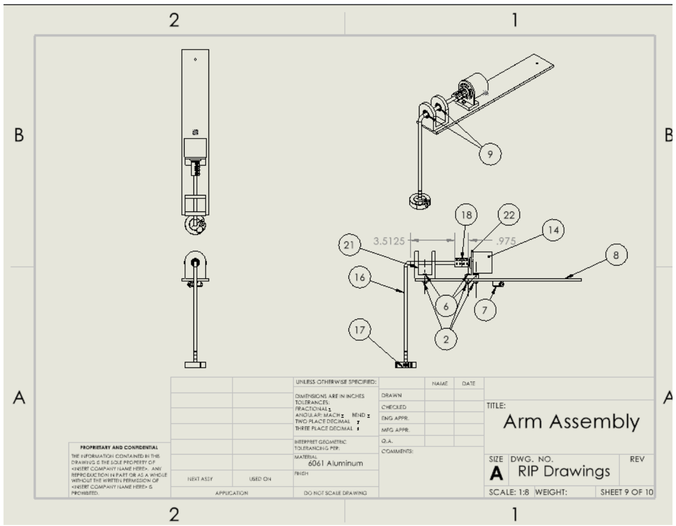
Appendix A: Bill of Materials

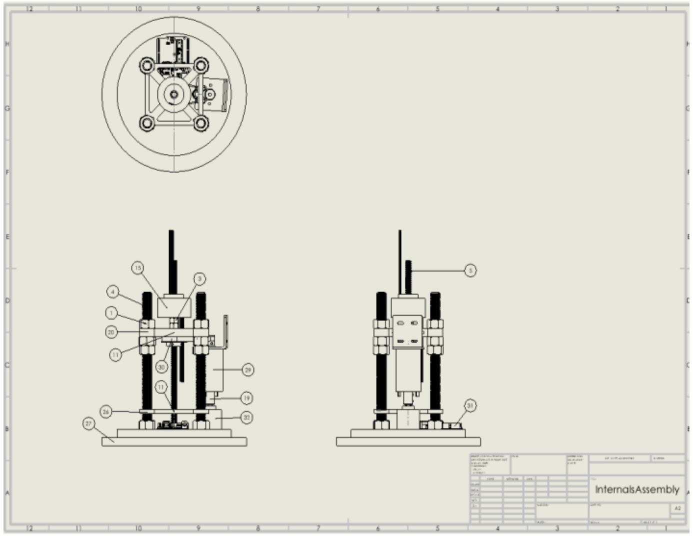
All detailed drawings utilize below BOM for part numbers and descriptions

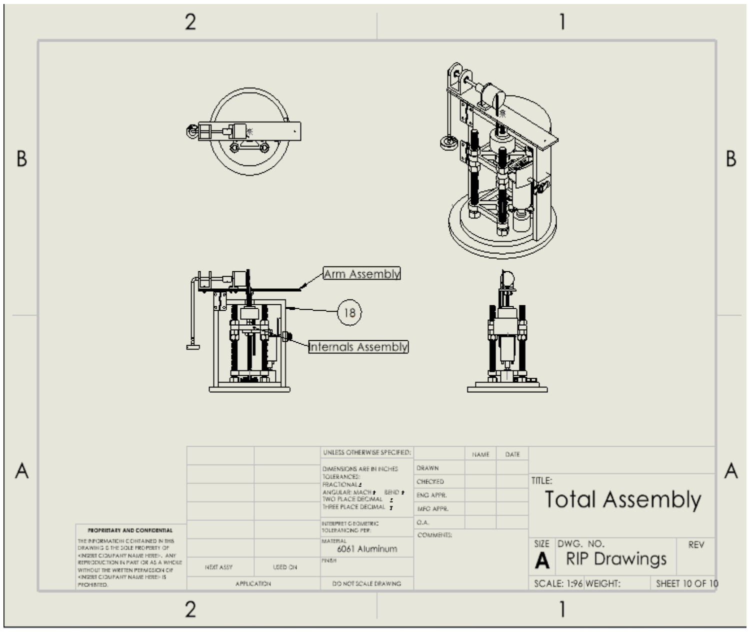


Part Number	Part Name	Quantity	Source	Cost($)	McMaster Code
1	5/8" Hex head nut	16	Lowe's	$24	N/A
2	6-32 Hex Head nut	Bulk	McMaster-Carr	4.81	91841A007
3	3/8" Hex Head nut	Bulk	McMaster-Carr	15.96	95462A031
4	9" Threaded bolt (5/8" diameter)	4	McMaster-Carr	83.16	92865a286
5	10" 3/8" diameter threaded rod	1	McMaster-Carr	11.02	90322A337
6	6-32 Bolt, 5/8" long	Bulk	McMaster-Carr	7.21	92314A150
7	Collar	1	McMaster-Carr	3.93	9946K13
8	Beam	1	McMaster-Carr	5.58	8975K696
9	Pendulum Bearing	2	McMaster-Carr	13.58	60355K151
10	3/8" washers	Bulk	McMaster-Carr	10.99	91860A031
11	3/8" Bearing	2	McMaster-Carr	13.1	60355K165
12	Hinge	2	Lowe's	4	N/A
13	Latch	1	Lowe's	6	N/A
14	Pendulum Encoder	1	Amazon	18.97	N/A
15	Slip Ring	1	Amazon	55.84	N/A
16	Shaft (Pendulum)	1	McMaster-Carr	12.64	2025K4
17	Pendulum Weight	1	McMaster-Carr	36	1511k24
18	Pendulum-Encoder Coupling	1	McMaster-Carr	31.38	61005K311
19	Motor-Encoder Coupling	1	Gavin Garner	5.33	
20	Upper Brace	1	printed	20.95	
21	Bearing Holder	1	printed	9.36	
22	Encoder Mount	1	printed	4.6	
23	Belt Tensioner	1	printed	0.98	
24	Belt Tensioner cap	1	printed	0.78	
25	Belt Tensioner bearing	1	scavenged	6.79	
26	Lower Brace	1	printed	10.43	
27	Bottom Base	1	Made by Momot	0	
28	Shroud Half	2	Made by Momot	0	
29	Motor	1	Momot	29.3	
30	Pulley and Belt	1	Momot	5.25	
31	Arduino	1	Momot	27.6	
32	Motor Encoder	1	Momot	$15	
33	H-Bridge	1	Gavin Garner	$11	
			Total	$506	

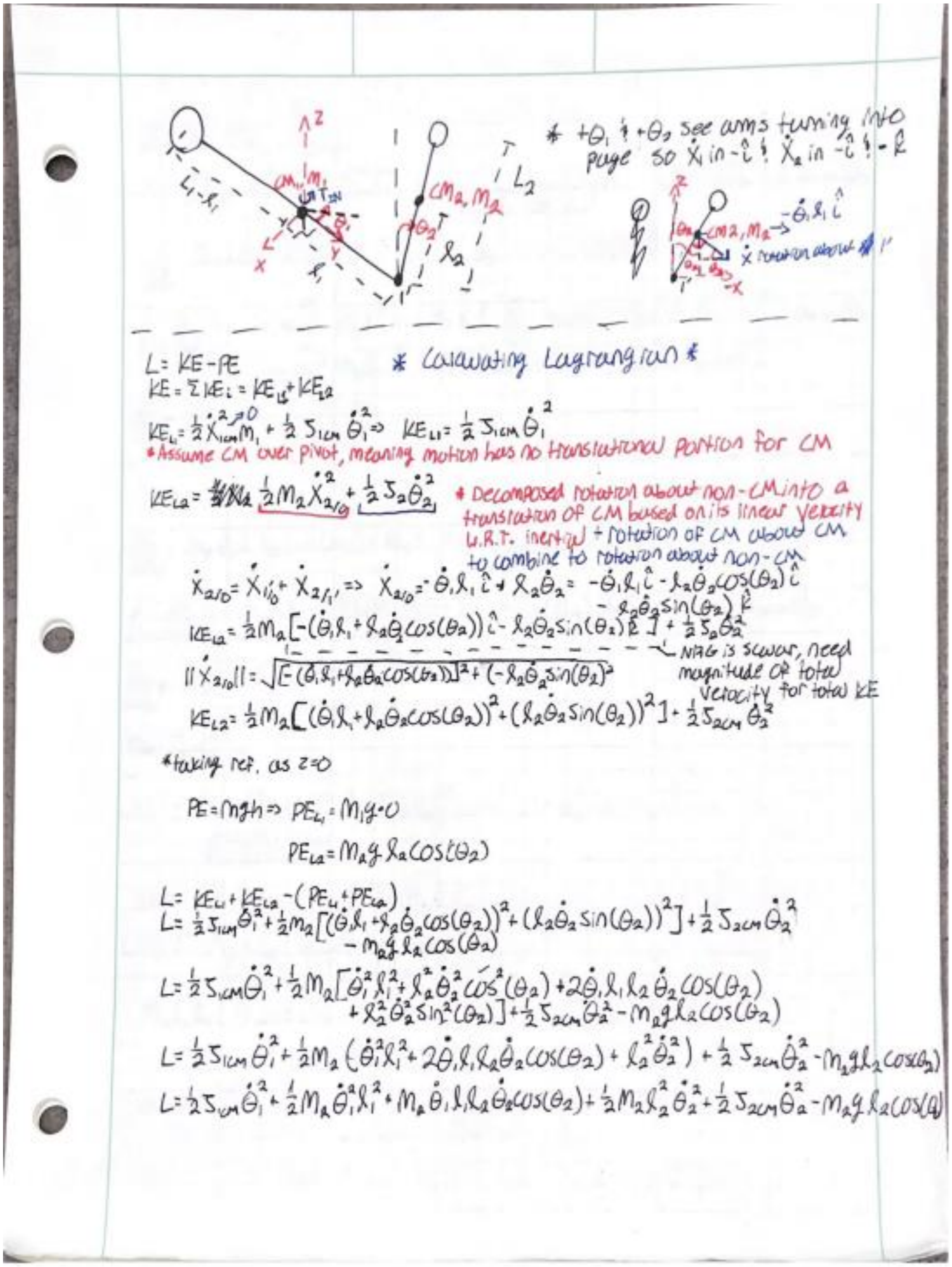
Appendix B: Assembly Drawings







Appendix C: Derivation for Equations of Motion



* $+\theta_1$ & $+\theta_2$ see arms turning into page so $\dot X_1$ in $-\hat i$ & $\dot X_2$ in $-\hat i$ & $-\hat k$

* Calculating Lagrangian *

$L = KE - PE$

$KE = \Sigma KE_i = KE_{L1} + KE_{L2}$

$KE_{L_1} = \frac{1}{2}\dot X_{1cm}^{2 \to 0} m_1 + \frac{1}{2} J_{1cm}\dot\theta_1^2 \Rightarrow KE_{L1} = \frac{1}{2} J_{1cm}\dot\theta_1^2$

* Assume CM over pivot, meaning motion has no translational portion for CM

$KE_{L2} = \underbrace{\frac{1}{2} m_2 \dot X_{2/0}^2} + \underbrace{\frac{1}{2} J_2 \dot\theta_2^2}$

* Decomposed rotation about non-CM into a translation of CM based on its linear velocity W.R.T. inertial + rotation of CM about CM to combine to rotation about non-CM

$\dot x_{2/0} = \dot X_{1'/0} + \dot X_{2/1'} \Rightarrow \dot X_{2/0} = -\dot\theta_1 l_1 \hat i + l_2\dot\theta_2 = -\dot\theta_1 l_1 \hat i - l_2\dot\theta_2\cos(\theta_2)\hat i$
$- l_2\dot\theta_2\sin(\theta_2)\hat k$

$KE_{L2} = \frac{1}{2} m_2\left[-(\dot\theta_1 l_1 + l_2\dot\theta_2\cos(\theta_2))\hat i - l_2\dot\theta_2\sin(\theta_2)\hat k\right] + \frac{1}{2} J_2\dot\theta_2^2$

MAG is scalar, need magnitude of total velocity for total KE

$\|\dot x_{2/0}\| = \sqrt{[-(\dot\theta_1 l_1 + l_2\dot\theta_2\cos(\theta_2))]^2 + (-l_2\dot\theta_2\sin(\theta_2))^2}$

$KE_{L2} = \frac{1}{2} m_2\left[(\dot\theta_1 l_1 + l_2\dot\theta_2\cos(\theta_2))^2 + (l_2\dot\theta_2\sin(\theta_2))^2\right] + \frac{1}{2} J_{2cm}\dot\theta_2^2$

*taking ref. as z=0

$PE = mgh \Rightarrow PE_{L1} = m_1 g \cdot 0$

$PE_{L2} = m_2 g l_2 \cos(\theta_2)$

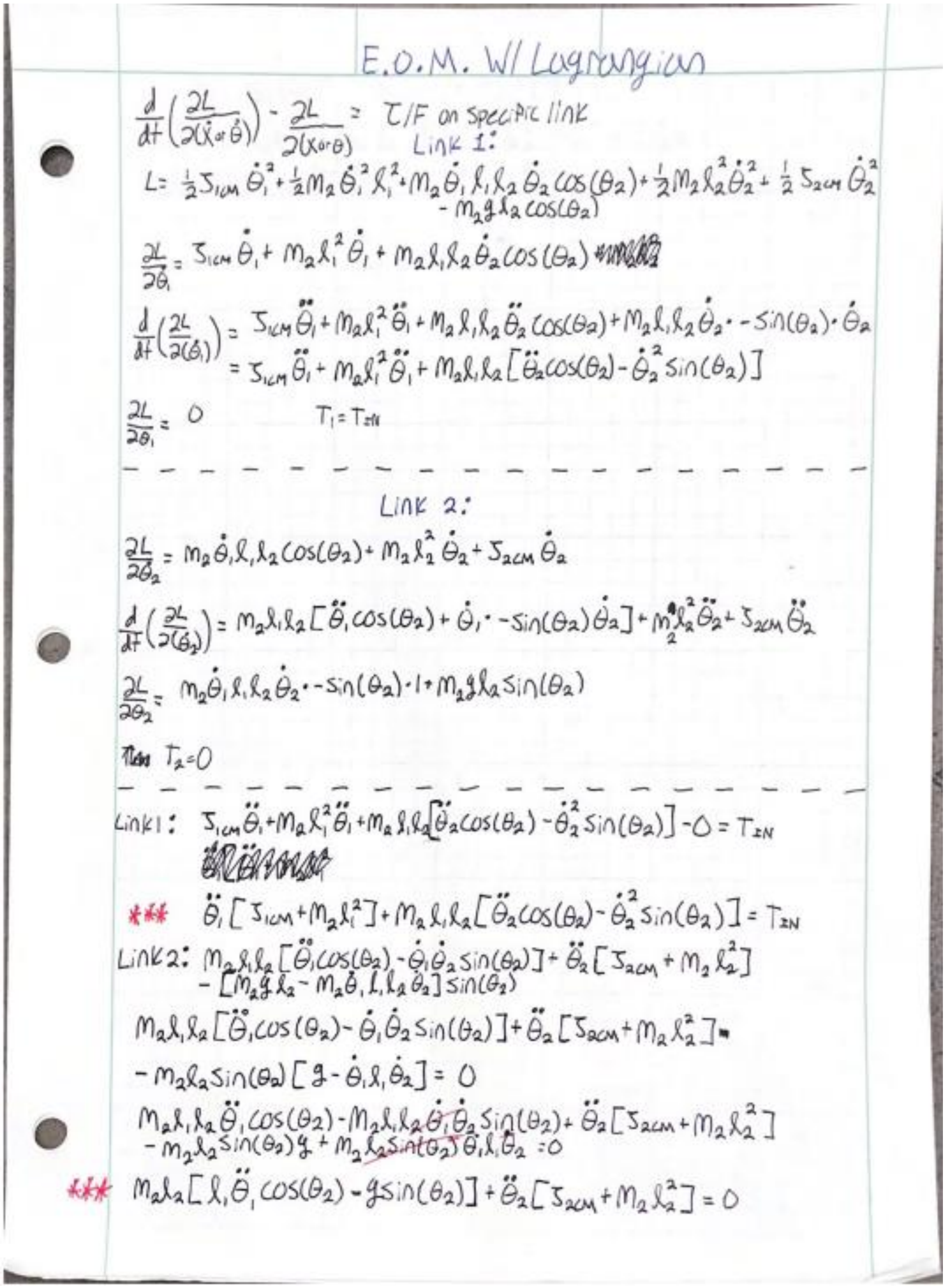
$L = KE_{L1} + KE_{L2} - (PE_{L1} + PE_{L2})$

$L = \frac{1}{2} J_{1cm}\dot\theta_1^2 + \frac{1}{2} m_2\left[(\dot\theta_1 l_1 + l_2\dot\theta_2\cos(\theta_2))^2 + (l_2\dot\theta_2\sin(\theta_2))^2\right] + \frac{1}{2} J_{2cm}\dot\theta_2^2$
$- m_2 g l_2\cos(\theta_2)$

$L = \frac{1}{2} J_{1cm}\dot\theta_1^2 + \frac{1}{2} m_2\left[\dot\theta_1^2 l_1^2 + l_2^2\dot\theta_2^2\cos^2(\theta_2) + 2\dot\theta_1 l_1 l_2\dot\theta_2\cos(\theta_2)\right.$
$\left. + l_2^2\dot\theta_2^2\sin^2(\theta_2)\right] + \frac{1}{2} J_{2cm}\dot\theta_2^2 - m_2 g l_2\cos(\theta_2)$

$L = \frac{1}{2} J_{1cm}\dot\theta_1^2 + \frac{1}{2} m_2\left(\dot\theta_1^2 l_1^2 + 2\dot\theta_1 l_1 l_2\dot\theta_2\cos(\theta_2) + l_2^2\dot\theta_2^2\right) + \frac{1}{2} J_{2cm}\dot\theta_2^2 - m_2 g l_2\cos(\theta_2)$

$L = \frac{1}{2} J_{1cm}\dot\theta_1^2 + \frac{1}{2} m_2\dot\theta_1^2 l_1^2 + m_2\dot\theta_1 l_1 l_2\dot\theta_2\cos(\theta_2) + \frac{1}{2} m_2 l_2^2\dot\theta_2^2 + \frac{1}{2} J_{2cm}\dot\theta_2^2 - m_2 g l_2\cos(\theta_2)$



E.O.M. W/ Lagrangian

$$\frac{d}{dt}\left(\frac{\partial L}{\partial(\dot{x} \text{ or } \dot{\theta})}\right) - \frac{\partial L}{\partial(x \text{ or } \theta)} = \tau/F \text{ on specific link}$$

Link 1:

$$L = \tfrac{1}{2}J_{1cm}\dot{\theta}_1^2 + \tfrac{1}{2}m_2\dot{\theta}_1^2 l_1^2 + m_2\dot{\theta}_1 l_1 l_2\dot{\theta}_2\cos(\theta_2) + \tfrac{1}{2}m_2 l_2^2\dot{\theta}_2^2 + \tfrac{1}{2}J_{2cm}\dot{\theta}_2^2 - m_2 g l_2\cos(\theta_2)$$

$$\frac{\partial L}{\partial\dot{\theta}_1} = J_{1cm}\dot{\theta}_1 + m_2 l_1^2\dot{\theta}_1 + m_2 l_1 l_2\dot{\theta}_2\cos(\theta_2)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial(\dot{\theta}_1)}\right) = J_{1cm}\ddot{\theta}_1 + m_2 l_1^2\ddot{\theta}_1 + m_2 l_1 l_2\ddot{\theta}_2\cos(\theta_2) + m_2 l_1 l_2\dot{\theta}_2\cdot -\sin(\theta_2)\cdot\dot{\theta}_2$$

$$= J_{1cm}\ddot{\theta}_1 + m_2 l_1^2\ddot{\theta}_1 + m_2 l_1 l_2[\ddot{\theta}_2\cos(\theta_2) - \dot{\theta}_2^2\sin(\theta_2)]$$

$$\frac{\partial L}{\partial\theta_1} = 0 \qquad T_1 = T_{IN}$$

Link 2:

$$\frac{\partial L}{\partial\dot{\theta}_2} = m_2\dot{\theta}_1 l_1 l_2\cos(\theta_2) + m_2 l_2^2\dot{\theta}_2 + J_{2cm}\dot{\theta}_2$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial(\dot{\theta}_2)}\right) = m_2 l_1 l_2[\ddot{\theta}_1\cos(\theta_2) + \dot{\theta}_1\cdot -\sin(\theta_2)\dot{\theta}_2] + m_2 l_2^2\ddot{\theta}_2 + J_{2cm}\ddot{\theta}_2$$

$$\frac{\partial L}{\partial\theta_2} = m_2\dot{\theta}_1 l_1 l_2\dot{\theta}_2\cdot -\sin(\theta_2)\cdot 1 + m_2 g l_2\sin(\theta_2)$$

$T_2 = 0$

Link1: $J_{1cm}\ddot{\theta}_1 + m_2 l_1^2\ddot{\theta}_1 + m_2 l_1 l_2[\ddot{\theta}_2\cos(\theta_2) - \dot{\theta}_2^2\sin(\theta_2)] - 0 = T_{IN}$

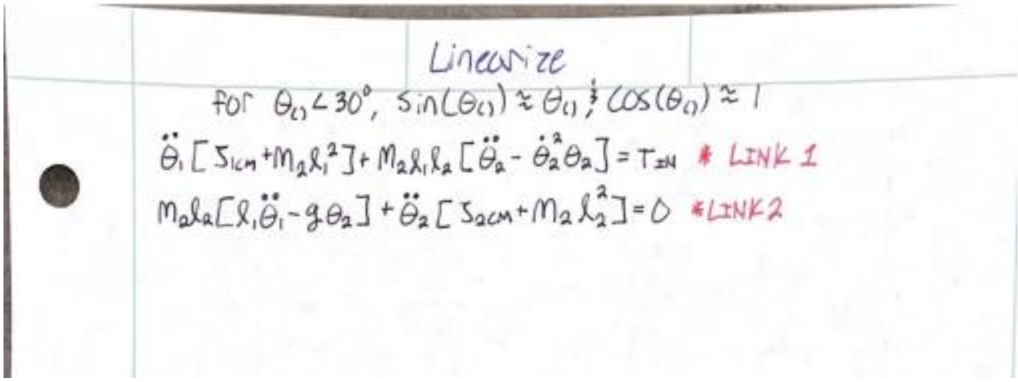
*** $\ddot{\theta}_1[J_{1cm} + m_2 l_1^2] + m_2 l_1 l_2[\ddot{\theta}_2\cos(\theta_2) - \dot{\theta}_2^2\sin(\theta_2)] = T_{IN}$

Link2: $m_2 l_1 l_2[\ddot{\theta}_1\cos(\theta_2) - \dot{\theta}_1\dot{\theta}_2\sin(\theta_2)] + \ddot{\theta}_2[J_{2cm} + m_2 l_2^2] - [m_2 g l_2 - m_2\dot{\theta}_1 l_1 l_2\dot{\theta}_2]\sin(\theta_2)$

$$m_2 l_1 l_2[\ddot{\theta}_1\cos(\theta_2) - \dot{\theta}_1\dot{\theta}_2\sin(\theta_2)] + \ddot{\theta}_2[J_{2cm} + m_2 l_2^2] - m_2 l_2\sin(\theta_2)[g - \dot{\theta}_1 l_1\dot{\theta}_2] = 0$$

$$m_2 l_1 l_2\ddot{\theta}_1\cos(\theta_2) - m_2 l_1 \cancel{l_2\dot{\theta}_1\dot{\theta}_2}\sin(\theta_2) + \ddot{\theta}_2[J_{2cm} + m_2 l_2^2] - m_2 l_2\sin(\theta_2)g + m_2\cancel{l_2\sin(\theta_2)}\dot{\theta}_1 l_1\dot{\theta}_2 = 0$$

*** $m_2 l_2[l_1\ddot{\theta}_1\cos(\theta_2) - g\sin(\theta_2)] + \ddot{\theta}_2[J_{2cm} + m_2 l_2^2] = 0$



Linearize

for $\theta_{()} < 30°$, $\sin(\theta_{()}) \approx \theta_{()}$; $\cos(\theta_{()}) \approx 1$

$\ddot{\theta}_1 [J_{1cm} + m_2 l_1^2] + m_2 l_1 l_2 [\ddot{\theta}_2 - \dot{\theta}_2^2 \theta_2] = T_{IN}$ * LINK 1

$m_2 l_2 [l_1 \ddot{\theta}_1 - g\theta_2] + \ddot{\theta}_2 [J_{2cm} + m_2 l_2^2] = 0$ *LINK 2

Appendix D: Acceleration of Pendulum Arm Derivation

$\sin(\theta_2)$ $\quad = \sin(\theta_1)\hat{i} + \cos(\theta_1)\hat{k}$

$$x_{cm2/A} = -l_2\cos(\theta_2)\hat{j} + l_2\sin(\theta_2)\cos(\theta_1)\hat{k} + l_2\sin(\theta_2)\sin(\theta_1)\hat{i}$$

$$\vec{x}_{cm2/A} = l_2[0\hat{i}' - \cos(\theta_2)\hat{j}' + \sin(\theta_2)\hat{k}'] = l_2[-\cos(\theta_2)\hat{j} + \sin(\theta_2)\sin(\theta_1)\hat{i} + \sin(\theta_2)\cos(\theta_1)\hat{k}]$$

$$\vec{\ddot{\theta}}_1 = \ddot{\theta}_1\hat{j}$$

$$\vec{\ddot{\theta}}_2 = -\ddot{\theta}_2[\cos(\theta_1)\hat{i} - \sin(\theta_1)\hat{k}]$$

$$\ddot{x}_{cm2/0} = \ddot{\theta}_1\hat{j} \times l_1[\cos(\theta_1)\hat{i} - \sin(\theta_1)\hat{k}] + -\vec{\ddot{\theta}}_2[\cos(\theta_1)\hat{i} - \sin(\theta_1)\hat{k}] \times l_2[\sin(\theta_2)\sin(\theta_1)\hat{i} - \cos(\theta_2)\hat{j} + \sin(\theta_2)\cos(\theta_1)\hat{k}]$$
$$+ -\dot{\theta}_2[\cos(\theta_1)\hat{i} + \sin(\theta_1)\hat{k}] \times [-\dot{\theta}_2[\cos(\theta_1)\hat{i} + \sin(\theta_1)\hat{k}] \times l_2[\sin(\theta_2)\sin(\theta_1)\hat{i} - \cos(\theta_2)\hat{j} + \sin(\theta_2)\cos(\theta_1)\hat{k}]]$$
$$-|\dot{\theta}_1^2 l_1| [\cos(\theta_1)\hat{i} + \sin(\theta_1)\hat{k}]$$

$$\ddot{x}_{cm2/0} = -\ddot{\theta}_1 l_1[\sin(\theta_1)\hat{i} + \cos(\theta_1)\hat{k}] - \ddot{\theta}_2 l_2[-\sin(\theta_1)\cos(\theta_2)\hat{i} + \sin(\theta_2)\hat{j} - \cos(\theta_1)\cos(\theta_2)\hat{k}]$$
$$+ |\dot{\theta}_2^2 l_2|[\sin(\theta_2)\sin(\theta_1)\hat{i} + \cos(\theta_2)\hat{j} - \sin(\theta_2)\cos(\theta_1)\hat{k}]$$
$$+ |\dot{\theta}_1^2 l_1|[\cos(\theta_1)\hat{i} - \sin(\theta_1)\hat{k}]$$

$$\ddot{x}_{cm2/0} = [-\ddot{\theta}_1 l_1\sin(\theta_1) + \ddot{\theta}_2 l_2\sin(\theta_1)\cos(\theta_2) - |\dot{\theta}_2^2 l_2|\sin(\theta_2)\sin(\theta_1) - |\dot{\theta}_1^2 l_1|\cos(\theta_1)]\hat{i}$$
$$+ [-\ddot{\theta}_2 l_2\sin(\theta_2) + |\dot{\theta}_2^2 l_2|\cos(\theta_2)]\hat{j}$$
$$+ [-\ddot{\theta}_1 l_1\cos(\theta_1) - \ddot{\theta}_2 l_2\cos(\theta_1)\cos(\theta_2) - |\dot{\theta}_2^2 l_2|\sin(\theta_2)\cos(\theta_1) - |\dot{\theta}_1^2 l_1|\sin(\theta_1)]\hat{k}$$

$A = -\ddot{\theta}_1 l_1 \qquad C = -|\dot{\theta}_2^2 l_2|$

$B = -\ddot{\theta}_2 l_2 \qquad D = -|\dot{\theta}_1^2 l_1|$

$$\ddot{x}_{cm2/0} = [A\sin(\theta_1) - B\sin(\theta_1)\cos(\theta_2) + C\sin(\theta_2)\sin(\theta_1) + D\cos(\theta_1)]\hat{i}$$
$$+ [B\sin(\theta_2) - C\cos(\theta_2)]\hat{j}$$
$$+ [A\cos(\theta_1) + B\cos(\theta_1)\cos(\theta_2) + C\sin(\theta_2)\cos(\theta_1) + D\sin(\theta_1)]\hat{k} \qquad *$$

$$\Sigma F = m_2\ddot{x}_{cm2/0} \Rightarrow F_{Ax} + F_{Ay} + F_{Az} - m_2 g = m_2\ddot{x}_{cm2/0}$$
$$F_{Ax} + F_{Ay} + F_{Az} = m_2[\ddot{x}_{cm2/0} + g]$$

$$\Sigma M_{cm2} = I_{cm2}\ddot{\theta}_2 \Rightarrow l_2[\sin(\theta_2)\sin(\theta_1)\hat{i} - \cos(\theta_2)\hat{j} + \sin(\theta_2)\cos(\theta_1)\hat{k}] \times F_{Ax}\hat{i} + F_{Ay}\hat{j} + F_{Az}\hat{k}$$
$$+ M_A = I_{cm2}\ddot{\theta}_2$$

$$I_{cm2}\ddot{\theta}_2 = l_2[(-F_{Az}\cos(\theta_2) - F_{Ay}\sin(\theta_2)\cos(\theta_1))\hat{i} + (F_{Az}\sin(\theta_2)\sin(\theta_1) - F_{Ax}\sin(\theta_2)\cos(\theta_1))\hat{j}$$
$$+ (F_{Ay}\sin(\theta_2)\sin(\theta_1) + F_{Ax}\cos(\theta_2))\hat{k}] + M_A$$

$$I_{cm2}\ddot{\theta}_2 = l_2 m_2[-\cos(\theta_2)[A\cos(\theta_1) - B\cos(\theta_1)\cos(\theta_2) + C\sin(\theta_2)\cos(\theta_1) + D\sin(\theta_1)]$$
$$- \sin(\theta_2)\cos(\theta_1)[B\sin(\theta_2) - C\cos(\theta_2)]]\hat{i}$$

$$I_{cm2}\ddot{\theta}_{2x} = l_2 m_2[-A\cos(\theta_1)\cos(\theta_2) + B\cos(\theta_1)\cos^2(\theta_2) - C\sin(\theta_2)\cos(\theta_1)\cos(\theta_2)$$

* M_A contains torque applied & reaction torque

$$\sum F = m\ddot{x}_1 = 0 \Rightarrow F_{A1} = -F_A \qquad l_1[\cos(\theta_1)\hat{i} + \sin(\theta_1)\hat{k}]$$

$$\sum M_{cm1} = \ddot{\theta}_1 I_{cm1} \Rightarrow \ddot{\theta}_1 I_{cm1} = \vec{X}_{A/O} \times F_A + M_A$$

$$\ddot{\theta}_1 I_{cm1} = l_1[\cos(\theta_1)\hat{i} + \sin(\theta_1)\hat{k}] \times [F_{Ax}\hat{i} + F_{Ay}\hat{j} + F_{Az}\hat{k}] + M_A$$

$$\ddot{\theta}_1 I_{cm1} = l_1[F_{Ay}\cos(\theta_1)\hat{k} - F_{Az}\cos(\theta_1)\hat{j} + F_{Ax}\sin(\theta_1)\hat{j} - F_{Ay}\sin(\theta_1)\hat{i}] + M_A$$

$$\ddot{\theta}_1 I_{cm1} = l_1[-F_{Ay}\sin(\theta_1)\hat{i} + (F_{Ax}\sin(\theta_1) - F_{Az}\cos(\theta_1))\hat{j} + F_{Ay}\cos(\theta_1)\hat{k}] + M_A$$

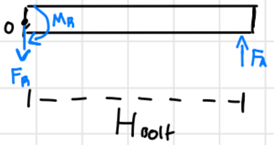
$$\ddot{\theta}_{1x} = 0, \ -l_1 F_{Ay}\sin(\theta_1) + M_{Ax} = 0, \ M_{Ax} = l_1 F_{Ay}\sin(\theta_1)$$

$$\ddot{\theta}_{1z} = 0, \ -l_1 F_{Ay}\cos(\theta_1) = M_{Az}$$

$$\ddot{\theta}_1 I_{cm1} = F_{Ax}\sin(\theta_1) - F_{Az}\cos(\theta_1) + \tau_A \Rightarrow \ddot{\theta}_1 = \frac{1}{I_{cm1}}[F_{Ax}\sin(\theta_1) - F_{Az}\cos(\theta_1) + \tau_{motor}]$$

$$[\ddot{\theta}_1 I_{cm1} + F_{Az}\cos(\theta_1) - F_{Ax}\sin(\theta_1)]\hat{j} = \tau_{motor}$$

Appendix E: Derived Spring Constant and Natural Frequency



$$q(X) = -F_B\langle X-0\rangle^{-1} + M_B\langle X-0\rangle^{-2} + F_A\langle X-H_{BOLT}\rangle^{-1}$$

$$V(X) = -F_B\langle X\rangle^{0} + M_B\langle X\rangle^{-1}$$

$$M(X) = -F_B\langle X\rangle^{1} + M_B\langle X\rangle^{0}$$

$$\theta(X) = \frac{1}{EI}\left[-\frac{F_B}{2}\langle X\rangle^{2} + M_B\langle X\rangle^{1}\right]$$

$$\delta(X) = \frac{1}{EI}\left[-\frac{F_B}{6}\langle X\rangle^{3}\right] + \frac{M_B\langle X\rangle^{2}}{2}\Big]$$

$$= \frac{1}{EI}\left[\frac{F_A}{6}X^3 - \frac{F_A H_B}{2}X^2\right] = \frac{X^2 F_A}{2EI}\left[\frac{X}{3} - H_B\right] = \delta(X)$$

$$\sum F = 0 \Rightarrow F_A + F_B = 0 \Leftrightarrow F_B = -F_A$$

$$\sum M_0 = 0 \Rightarrow M_B + H_{Bolt} F_A = 0$$

$$M_B = -F_A H_{BOLT}$$

$$I_x = I_y = \frac{1}{4}\pi \cdot {\frac{5}{16}''}^{4} =$$

$$E_{steel} = 30 \cdot 10^6\, psi$$

$$H_{BOLT} = 5''$$

$$M = 3\ lb$$

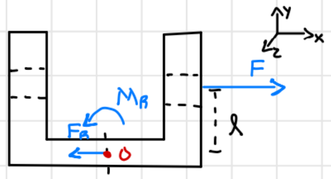
$$\frac{F_A}{\delta} = \frac{2EI}{X^2\left[\frac{X}{3} - H_B\right]} \Rightarrow \frac{F_A}{\delta} = \frac{2EI}{H_B^3 \cdot -\frac{2}{3}} \Rightarrow \frac{F_A}{\delta} = \frac{-3EI}{H_{Bolt}^3}$$

$$\frac{F_A}{\delta} = K = 5393 \qquad \frac{lbf}{in} = 5393 \qquad \frac{\frac{slug \cdot in}{s^2}}{in} = \frac{slug}{s^2}$$

$$\omega_n = \sqrt{\frac{K}{M}} \Rightarrow \omega_n = \sqrt{\frac{5393\ slug/s^2}{3 \cdot 32.2\ slug}} = 47\ \frac{rev}{sec}$$

$$\omega_n = 47\ \frac{rev}{sec}$$

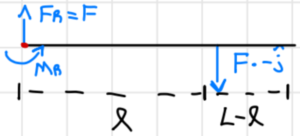
Appendix F: Simple Stress Calculations for Weakest Portion of the System



* Assume worst case loading all force taken up by one bearing.

$$\Sigma F_x = 0 \Rightarrow F + F_B = 0 \Rightarrow F_B = -F$$

$$\Sigma M_o = 0 \Rightarrow \ell \cdot \hat{j} \times F \cdot \hat{i} + M_B = 0 \Rightarrow -F\ell\hat{k} + M_B = 0 \Rightarrow M_B = F\ell\hat{k}$$

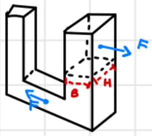


$$W(x) = F\langle x-0\rangle^{-1} - F\ell\langle x-0\rangle^{-2} - F\langle x-\ell\rangle^{-1}$$

$$V(x) = \int W(x)dx = F\langle x\rangle^{0} - F\ell\langle x\rangle^{-1} - F\langle x-\ell\rangle^{-1}$$

$$M(x) = \int V(x)dx = F\langle x\rangle^{1} - F\ell\langle x\rangle^{0} - F\langle x-\ell\rangle^{0}$$

$$M(0) = -F\ell$$



$$\sigma_{Bend} = \frac{M_I C}{I}, \quad \sigma_{B.max} = \frac{F\ell\frac{B}{2}}{\frac{1}{12}B^3H} = \frac{6F\ell}{B^2H} \downarrow$$

(Nominal Vals.)

$$\tau \approx \frac{F}{A_{\parallel F}} = \frac{F}{BH} \longrightarrow$$

$$\sigma_{B.max} = K \cdot \frac{6F\ell}{B^2H}$$

$$\tau \approx K \cdot \frac{F}{BH}$$

$S_{y(ABS)} \approx 4351$ Psi, $S_{y(Alum\ 6061)} \approx 17997$ Psi * Wood is very anisotropic, if loads signif stay away

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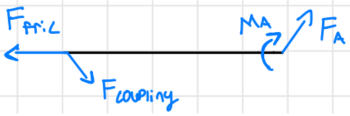

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Sukontanak, V., & Parnichkun, M. (2009). Real-time optimal control for rotary inverted pendulum. *American Journal of Applied Sciences*, *6*(6), 1106–1115. https://doi.org/10.3844/ajassp.2009.1106.1115

The Effects of Automation and Robotic Presence on Unemployment and the Economic Health of Workers Both on a Large Scale and Individual Basis

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

Jimmy Garza
Spring 2024

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor
Pedro A. P. Francisco, Department of Engineering and Society

Introduction

A hot topic of modern debate in today's economy and workforce is the uprising and potential replacement of manual jobs by industrial robots. As far back as 1929, economists and scholars had bold predictions that a new form of economic instability, dubbed "technological unemployment" would sweep across the developed world alongside other wage imbalances and inequalities (Keynes, 1931). This fear has proven to be more than just an overreaction to a fear of a future technologically controlled dystopia brought on by traditionalists. In fact, there is mounting evidence suggesting that, while not the drastic economy bending force it has the potential to be yet, modern advances in automation and robotics have already created or worsened wage imbalances between various working classes and different industries (Autor, Levy, and Murnane 2003).

My research question is as follows: What are the effects of automation within the United States workforce on both large scale and individual levels? The conclusions drawn from the research within this paper will be entirely quantitatively based in statistics and survey information. There is another side to the impacts of automation in industry, that being the qualitative benefits to worker satisfaction and happiness that are impossible to accurately quantify without extensive polling. Even then, things like happiness and contentedness are difficult to objectively scale. As such, these aspects of the evolving industries of America will not be considered.

The goal of the following paper is to give a very simple analysis on the impacts of robots being introduced into the workforce on American worker wellbeing. This paper will consider various metrics when determining overall economic health of the United States as well as individual worker health and effects. I will consider economic impacts on groups pertaining to gender, economic status, education, and age.

Background

As defined by the International Federation of Robotics, an industrial robot is: "an automatically controlled, reprogrammable, and multipurpose machine," (International Federation of Robotics, n.d). The line that defines what an industrial robot actually is can be slightly ambiguous at times, as the multipurpose nature of the definition can be difficult to interpret. Commonly agreed upon examples of industrial robots are: Robotic welders, autonomous painting machines, and assembly machines whose motions can be altered depending on the product being produced are all considered solid examples of an industrial robot.

It is reasonable to expect that in the presence of companies making more money and producing more of their products that workers within that company would see higher raises, bonuses, and starting salaries for newly employed workers (Rotman, 2013). However, there is evidence suggesting that increased wages over the past few decades are entirely concentrated in the upper 10% of earners in the United States (Congressional Research Center, 2020).

This economic boom in a small area has the potential to create jobs due to industry expansion as well as the necessity of new jobs handling, maintaining, and otherwise keeping tabs on the newly implemented automated systems. However, if it is the case that automation has been creating more and more displacement of workers that originally worked those low skilled jobs, even if more jobs are created than are destroyed the workers that were originally displaced by the effects of automation will still likely struggle to find new employment as they are unqualified to fill the created positions like machinery technicians (Dizikes, n.d.).

Methodology

I looked into my STS problem statement through the use of the actor network theory (ANT) framework. I will be using ANT to research the effects of automation on job diversity and unemployment in affected industries. I considered my problem in the scope of actor network theory as my questions are heavily dependent on the relationships between various components of a larger whole. The ANT framework has us considering everything within our given system as interacting with one another in a series of individual relationships. Everything, from human beings, to tools and other objects, to ideas and processes are all considered as actors within the network we are considering. As such, every single actor in our network has the capability to impact a social precedent or any other relationship within the network. The ANT framework works so well for my problem because analysis of unemployment rates, worker wages, worker displacement, productivity rates, and various other metrics by which I will be considering automation's impacts on economic relations is very dependent on numerous small interactions between affected parties. To fully characterize why these individual metrics are changing, it is extremely important to understand how each of these metrics interact with one another, as well as how they interact with each player in the network. Automation may destroy more jobs than it creates, but if the wages of the workers that are not cut increase threefold, then it can become a little more complicated to determine if it is overall a good thing.

In my analysis of this problem, I will be collecting data and analyzing trends within two very distinct situations. Firstly, I will be looking at how automation has affected economic profitability and employment rates on a large scale across the United States. I will be considering metrics such as the US GDP in order to determine company productivity. Additionally I will be considering how country-wide employment rates shifted during times where robots were rapidly becoming part of the workforce. Ideally quantifying industrial productivity and the impacts automation had on potentially displaced workers over time periods where robotic presence in the workforce was heavily changing will give insight into the net effects of automation for the country.

I will also be considering these same effects on a much more individual scale. I will be considering unemployment rates within lower earning workers whose jobs are more likely to be replaced by robotic systems and analyzing whether or not any trends arise during eras of high automation. I will then consider how individual wages and salaries of workers within companies undergoing automation change, but I will specifically be comparing wage changes of workers within lower paying jobs within their respective companies, such as assembly line workers or warehouse staff, to workers in the upper levels of a company, such as designers or CEOs whose jobs are not at risk of being overtaken by robotic systems. In doing this I hope to highlight whether or not those workers whose jobs are actually impacted by automation are negatively impacted while those who run the companies reap immense rewards alone.

Literature Review/Results

It is estimated that the introduction of some robotic system into a workplace eliminates 6 jobs from that area (Brown, 2020). On the flip side of this, Brown also makes the claim that automation has been seen to increase productivity and efficiency, improving profits for companies and generally increasing economic health in the areas that are automated. These seemingly inverse effects are extremely difficult to diagnose as solely being related to automation (Rotman, 2013). As this happens worker wages are expected to increase. Also, this economic boom in a small area has the potential to create jobs due to industry expansion as well as the necessity of new jobs handling, maintaining, and otherwise keeping tabs on the newly implemented automated systems.

Predictive models such as one from "Automations Impacts on China's Job Market", suggests that if automation is to continue in China, entire cities would become entirely specialized in either automated fields like manufacturing and textiles or they would become solely focused on fields that are not able to be automated. There would be no overlap between industries in the same city (Chen et al., 2021). These implications have interesting implications for the potential of an automated future. Based off of trends used within the model, the predictive model suggests that within these automation friendly super cities, human involvement in the industry itself would approach a minimum. Outside of managerial and other social positions, most other jobs within these cities would cease entirely.

In another such model, it was predicted based off of historical wage and automation data that increasing automation levels across industries would end up decreasing worker wages as skilled workers could more easily be replaced with machines (Arnoud, 2018). The author refers to this potential phenomenon as a "decrease in worker bargaining power". If automation technology continues to evolve and advance, installation costs, operation costs, and maintenance costs of these new technologies will likely decline. Simultaneously, the increase in efficiency will allow the cost of manufactured products to decrease, incentivizing purchase and increasing company profits. As the capabilities for companies to implement automative technologies becomes more and more financially feasible, Arnoud argues that companies can then cut worker wages with little repercussion to the company. If workers go on strike or halt production, automative technology can easily be installed, replacing the workers. A similar situation can arise from workers asking for pay increases, better benefits, etc.

In a series of hearings presented to the United States Subcommittee of Education and Labor, real data from the United States Bureau of Labor Statistics was compiled detailing critical economic metrics within the steel manufacturing industry from the years of 1938 to 1960. During this time, the industry was undergoing massive automation advances that allowed the production of steel to become quicker, more cost effective, and capable of supplying much larger quantities (Committee on Education and Labor, 1961). This ended up making the profitability of the industry as a whole reach all-time highs year after year. Not only were employee salaries collected and presented during this hearing, but other more unassuming metrics were also presented. The total number of employees across the industry was collected, as well as the recorded hours worked for an annum.

In Erik Brynjolffson's article "The Great Decoupling", he discusses a concerning trend brought on by automation within the workforce. Historically, as jobs became more productive via the introduction of automation technology or scientific advances, the loss of jobs in automated fields was offset by the increase of wealth brought about by these advances. Unemployed workers were rapidly hired and picked up by the slew of other new companies created due to the influx of wealth into the economy. This trend was ideal for both workers and the companies they worked for. Companies were able to maximize profits and extend their spheres of influence, while workers were able to enjoy increased wages and employment opportunities as a direct result of a more healthy and competitive economic market. This trend saw private employment rates go up while closely following the overall GDP of the United States, up until the turn of the 21st century. Around this time, GDP continued to increase as private employment rates stagnated. This is what became known as "The Great Decoupling". This trend suggests that modern technology is so inexpensive and readily available that the increased business ventures available to companies as a result of technology production increases are no longer requiring substantial numbers of new jobs to be created to pilot the new companies and products. Paired with the reasonable idea that automation will only become more readily available, this decoupling suggests that eventually private employment will decrease as jobs that were originally streamlined or aided by technology get totally replaced and become obsolete (Brynjolffson, 2013).

In 2022 alone, industrial robot installations were up 10% of what was the total amount within the workforce at the time. This translated to just shy of 40,000 robots being added to the workforce during the year. During this year, the automotive industry was the largest contributor to automation growth, with almost 50% of the total robotic installations being related to the industry. Both metal production/manufacturing and electronics manufacturing were the next two largest industries for automation, with each having almost 13% of that year's automation increases associated with their industry (IFR International Federation of Robotics, n.d.).

It is estimated that the introduction of some robotic system into a workplace eliminates 6 jobs from that area (Brown, 2020). On the flip side of this, automation has been seen to increase productivity and efficiency, improving profits for companies and generally increasing economic health in the areas that are automated. Timmer found that in a decade span from 1995 to 2005 United States productivity increase because of automation was around 1% (Graetz, 2015). This translates to an increase in money flow throughout the US of tens of billions of dollars each year.

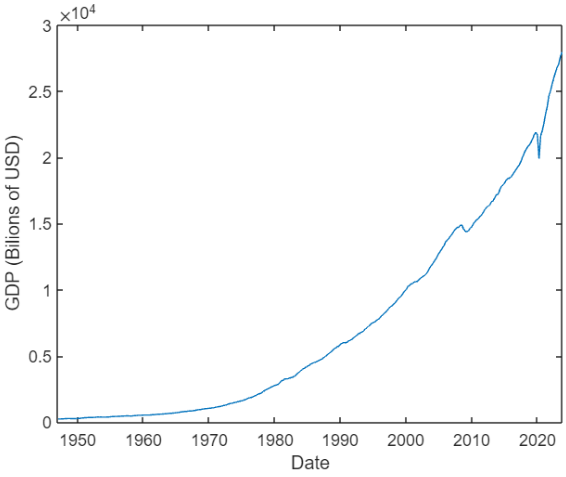

Fig. 1: US GDP Over Time

I initially looked at the United States GDP from 1947 to the end of 2023 to find the change in order to gauge increases in industrial productivity, which can be seen in figure 1. The data for this analysis, and all other within this paper unless otherwise specified, was pulled from the St. Louis Federal Reserve Database FRED. This value incorporates all facets of American manufacturing and production, not just those areas undergoing heavy automation, but automation can likely be attributed with being a major cause of the change. The percent change in American GDP from 1979 to 2023 came in at 113.97%, meaning that the amount of goods produced by the nation more than doubled across that small time frame. It is a reasonable assumption to make that this increase in production across the United States is largely due to the widespread usage of computers and the increased amounts of robotic workers within the workforce.

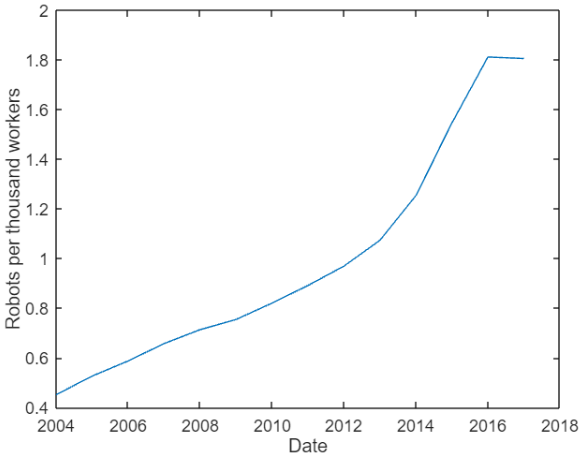

Fig. 2: Robot Intensity Over Time

The increase in country-wide productivity is likely due to automation increases, suggesting that the addition of robots into the workforce is extremely effective at increasing company production and profits. A study performed by the International Federation of Robotics (IFR) shows yearly increases in the number of robots within the workforce. The data can be found tabulated in appendix A, and graphically represented in figure 2. The robotic intensity, or the number of robots present in a surveyed metropolitan area per thousand workers, has almost perfectly quadrupled from .451 to 1.805 robots per thousand workers from 2004 to 2017.

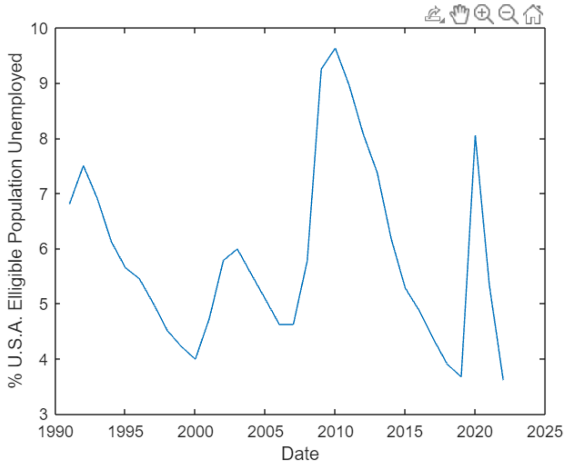

Fig. 3: US Unemployment Rate Over Time

I was unable to find reliable data on robotic intensity rates for any time frame prior to 2004, but the trend of steady increases in robot presence within the workforce was likely present well before the 2000's.

When considering the rate of unemployment change across the past three decades, it has not drastically changed. This data can be seen in Figure 3, and it suggests that the ratio of eligible working people in America to the number of employed people did not steadily shift upwards or downwards during this time. When analyzing the prior three figures together, it should be noted that during the years past 1990, the steady and rapid increase in robotic intensity, corresponding to a steady and rapid increase in US GDP, does not correspond to any quantifiable change in United States unemployment. If we consider that the US population only increased by around 50% during this time, then the overall productivity of the working class of Americans must have drastically gone up for a 50% increase in workers to correlate to a doubling of the American GDP. Looking at unemployment across the entirety of the United States seems to suggest that increased introduction of robots into the workforce did not cause a pronounced displacement of workers countrywide.

An analysis of the individual annual median wage of American workers from 1974 to 2019 can be seen in figure 4. The median annual individual income increased from 1974 to 2019 by $13,490. All values were adjusted to 2019 values of the dollar. This metric suggests that the very middle of earners in the United States made substantially more money in 2019 than they would have in 1974. This is not a perfect metric to determine whether a class of workers is experiencing wage shift, as it fails to represent things like gender and race, which have played huge roles in wages during the respective time frame. Despite these

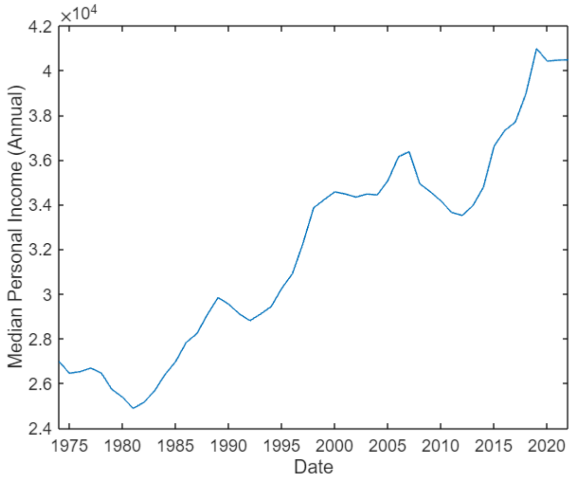

Fig 4: Median Income over Time

shortcomings, this metric would suggest that somebody in the middle class of workers is making substantially more money than they originally were.

An analysis was performed by the United States Congressional Research Service using data collected from the Current Population Survey (CPS) describing wage changes of workers from 1979 to 2019 separated by the percentile that each group of workers fit into in terms of overall income. There were three “levels” of earners, a low wage group where members were at or below the 10th percentile of income, a middle group where members sat between the 45th and 55th percentile of earners, and a high group where members were at or above the 90th percentile of earners. The individual median annual income for workers in the bottom 10% and top 10% of earners in the United States revealed huge disparities in the experienced wage changes across the wide range of American earners during this time frame. The collected data can be found tabulated and graphed in Appendices B and C, and the collected data for men in the bottom 10th percentile of earners can be seen in figure 5.

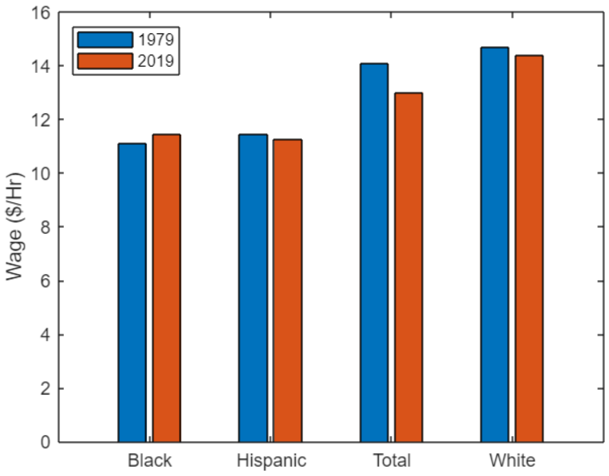

Fig. 5: Wage Shifts by Race Over 40 Years

A brief look at these changes reveals that workers in the bottom 10% of earners, whose jobs are most often displaced and impacted by automation technologies, were likely to experience a decrease in their wages. Overall (excluding race and ethnicity) men in this percentile of earners made $1.09 less in 2019 than they did in 1979. Women on the other hand made $0.99 more. Considering only earners making more than the 45th percentile and less than the 55th percentile, what will be referred to as near the 50th percentile, reveals a similar situation to the bottom 10th percentile earners. Women’s hourly wages in this range increased by $4.68 while men’s wages decreased by $0.79.

During this same time frame, men and women in the upper 10th percentile of earners wages skyrocketed. Men's hourly wages during the period between 1979 and 2019 jumped up by $18.47 overall. Women's wages increased by $20.20 as well. These numbers present stark contrasts to the changes seen in the lower earner percentiles, and the rates of change over the 40 year timeframe can be found in Appendix D. This would suggest that the productivity increases created as a result of robots being added to the workforce are resulting in wage increases and economic boons for less than half of the working class at a minimum. This is hardly the proposed economic gains that would offset and account for the unemployment increases in industries heavily impacted by automation. Another trend suggested by the data was that a worker's race/ethnicity heavily impacted the wage shift they could expect to see during this time frame.

In a study performed by The Century Foundation while analyzing Midwestern manufacturing industries growth and shifts since the Great Recession, the introduction of robots into the workforce were found to significantly harm the employment rates of young, less-educated men and women working within these manufacturing industries. The study showed a decrease in the employment-to-population ratio of the industry by about 3.5%. Additionally, this study suggested that for every additional robot added to the workforce per thousand workers, the workers experienced a 4-5% decline in their wages. This hyper localized scale research into the effects automation in the workplace is a double-edged sword. The small-scale data collection likely cannot capture what the "average" experience in such a situation would be. On the other hand, in this specific situation it gives great insight into how workers could be affected devoid of other large scale societal changes and outlier effects that are inherent to a large scale study.

Conclusion

Drawing conclusions about this topic is a very complex thing to attempt, as the United States job market is such a volatile and complicated thing. However, based off of the literature review I conducted and the data that I collected and analyzed, there are some apparent trends to be discussed pertaining to my STS questions: What are the effects of automation within the United States workforce on both large scale and individual levels and how do robots in the workforce impact the United States economy on a global scale?

Firstly, on a country- wide scale the introduction of robots into the workforce and the increased robotic intensity within the American workforce have increased the productivity and profitability of a lot of industries. The GDP increases seen since the turn of the 20th century show very concretely that the United States has heavily increased its productivity over time. Paired with the relatively similar workforce size between the turn of the century and now and the notable and rapid rate of robotic intensity increase at the turn of the century, I am inclined to trust that the addition of robotic aid into the workforce and, as a result, the increased automation of viable industries has and will continue to beneficially stimulate the American economy and by extension its many businesses and corporations at a rapid rate. On a country-wide and global scale, automating our industries has had immensely lucrative effects both efficiency wise and monetary wise. I fully expect the trend of automation to continue as AI systems and electronics continue to become better and more viable for industry.

The United States overall increase in individual annual income appears to speak to automation benefitting lower skill workers, but I suspect that this value is heavily skewed by strides over recent strides in companies to equalize pay across genders and races. Considering men in the middle level of earners increased their wages by less than a dollar, I suspect that the apparent increase in median wage is majorly because of women being paid more reasonable and fair wages compared to their male counterparts.

As far as unemployment effects are concerned, automating our industries seems to not have significant impacts as well. Of course, unemployment is incredibly difficult to tie specifically to a single industry factor or variable, but considering United States rates over the past decades suggests that in this era of rapid automation, humans are not being replaced and displaced from their jobs. On a country-wide scale, increased automation seems to have little impact on overall employment rates. The implications of this will be discussed when considering automation's effects on a more individual level.

In terms of economic effects on workers within these industries facing automation, the benefits seem much less ideal than those of the corporations. The lack of notable wage increases for middle- and lower-class workers while upper class wages skyrocket suggest automation benefits are focused solely at the top of companies and businesses. The slight decline in wages even suggests that automation may be lessening worker wage bargaining abilities, which could have dire implications in the future as robotic intensity increases more and more. I would say that automation appears to be actively hurting workers and laborers whose jobs compete with robotic systems in terms of wages.

Considering employment effects that automation seems to have on an individual level, it yet again does not appear to bode well for the laborers whose skills compete with robots. The statistics previously discussed suggest that these unskilled laborers are indeed becoming displaced by automated systems, and unable to find jobs within their skill set due to robots being more efficient and economically effective. Considering the country-wide unemployment rates seemingly not reflecting these losses of jobs, I consider two reasonings behind these seemingly paradoxical trends plausible.

Firstly, it could be that the increased unemployment within low-skilled laborers, brought on by automated systems fully taking their jobs over, is being offset by the creation of jobs designing, maintaining, and installing these new machines. This scenario may seem beneficial overall, but in all likelihood in the event of this scenario being correct the displaced workers would not be the ones filling in these new positions. Instead, this scenario would likely see an increased unemployment rate of low skilled workers whose jobs can now be done by machines and who lack skills and education necessary to move into other more skill-oriented positions, while previously unemployed engineers, machinists, and designers experience newfound employment due to the increased need for their training and expertise. This would even more heavily disadvantage lower class earners in terms of both wages and employment opportunities.

Secondly, it is possible that the increased money within the American economy could allow lower skilled, less educated workers easier access to education and further training programs. As a result, their displacement from their jobs could be kickstarting these workers into gaining skills necessary for movement into new fields and areas that are less susceptible to automation influences.

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Appendices

Appendix A: Robot Intensity from 2004 to 2017

Year	Intensity
2004	0.451
2005	0.526
2006	0.587
2007	0.657
2008	0.713
2009	0.754
2010	0.82
2011	0.891
2012	0.969
2013	1.073
2014	1.253
2015	1.545
2016	1.811
2017	1.805

Appendix B: Wage Differences of Women of Varying Race Between 1979 to 2019

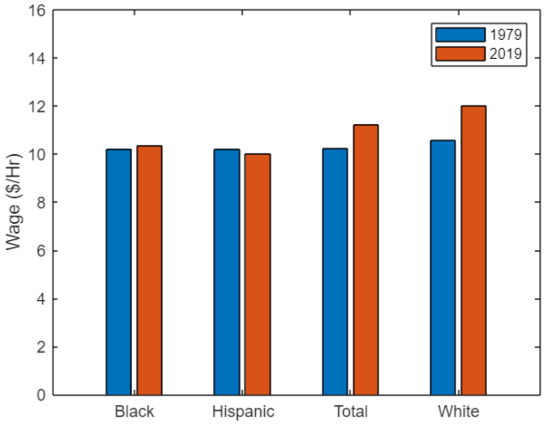

Fig. 6: Wage Change for Women in Lower 10th Percentile

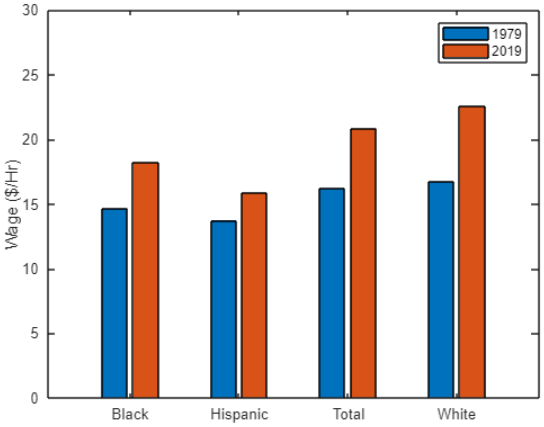

Fig. 7: Wage Change for Women in Near 50th Percentile

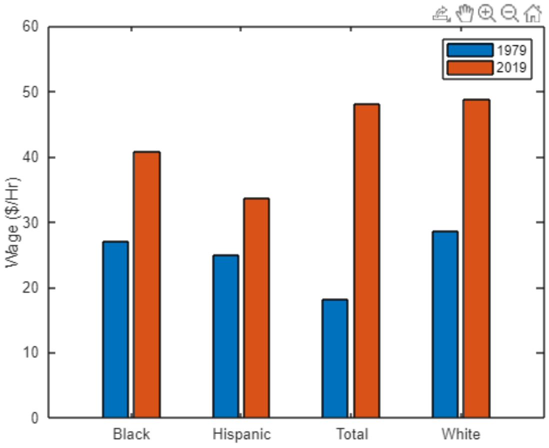

Fig. 8: Wage Change for Women in Upper 10th Percentile

Appendix C: Wage Differences of Men of Varying Race Between 1979 to 2019

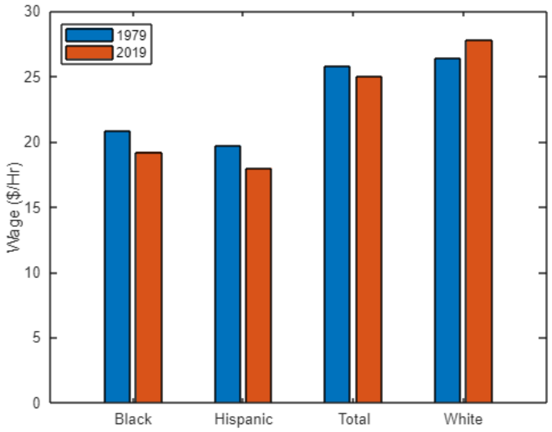

Fig. 9: Wage Change for Men in Near 50th Percentile

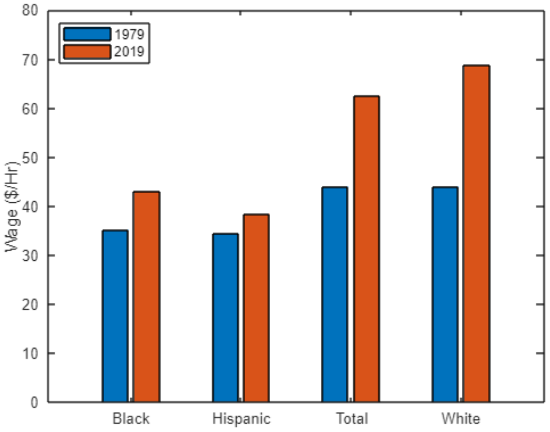

Fig. 10: Wage Change for Men in Upper 10th Percentile

Appendix D: Percent Change in Wages for Men of Varying Earnings from 1979 to 2019

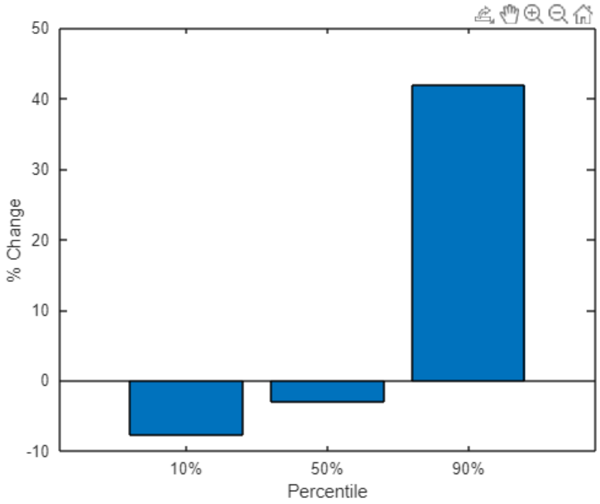

Fig. 11: Percent Change of Men's Wages Based on Earning Percentile

Engineering an Effective Linear Controller for a Rotary Inverted Pendulum

The Effect of Automation on Unemployment and Job Diversity

A Thesis Prospectus

In STS 4500

Presented to

The Faculty of the

School of Engineering and Applied Science

University of Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science in Mechanical Engineering

By Jimmy Garza

November 3, 2023

Technical Team Members: Charles Wermter, Aaron Seymour

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

ADVISORS

Prof. Pedro Augusto P. Francisco, Department of Engineering and Society Prof. Michael Momot, Department of Mechanical and Aerospace Engineering

Introduction

My overall research topic is automation technologies. Modern day industries are being automated at a rapid rate, introducing more robotic systems into the workplace than ever before. With modern strides in controls work as well as artificial intelligence and algorithms, more and more jobs are becoming capable of being automated. The effects and implications of what automation could do to the current workforce is poorly understood at best. I will be looking into the creation and applications of these technologies with my technical research portion: The creation of a rotary inverted pendulum (RIP) and a corresponding linear controller. I will be researching automation's effects and implications as part of my STS portion: The effect of automation on unemployment and job diversity in automated industries.

My technical project of engineering the RIP and, more specifically, it's necessary controller will demonstrate the awesome degree to which modern robots are capable of taking in various inputs of data from their surroundings and utilizing said data to perform a changing task within specific guidelines. Future AI systems capable of adapting their logic to inputs paired with controls systems that are capable of adapting their functions and modifying the outputs they are capable of producing could be the future of robotic systems. These systems have the potential to perform tasks that humans currently do at much quicker and more precise rates, which could lead to a massive increase in the presence of automated processes within the workplace. It is still somewhat unclear what the full effects of automation within the workplace are, however. This uncertainty necessitates looking into the relationships between workers, robotic systems, and the economy to determine if unchecked automation is fine to leave unchecked or if there is a necessity to create ,implement, and strengthen policies and programs to check automation's negative side effects.

I will be looking into my STS problem statement through the use of the actor network theory (ANT) framework. I will be using ANT to research the effects of automation on job diversity and unemployment in affected industries. I have decided to consider my problems in the scope of actor network theory as my problems are heavily dependent on the relationships between various components of a larger whole. The ANT framework has us considering everything within our given system as interacting with one another in a series of individual relationships. Everything, from human beings, to tools and other objects, to ideas and processes are all considered as actors within the network we are considering. As such, every single actor in our network has the capability to impact a social precedent or any other relationship within the network. The ANT framework works so well for my problem because analysis of unemployment rates, worker wages, worker displacement, productivity rates, and various other metrics by which I will be considering automation's impacts on economic health is very dependent on numerous small interactions between affected parties. To fully characterize why these individual metrics are changing, it is extremely important to understand how each of these metrics interact with one another, as well as how they interact with each player in the network. Automation may destroy more jobs than it creates, but if the wages of the workers that are not cut increase threefold, then it can become a little more complicated to determine if it is overall a good thing.

Engineering an Effective Rotary Inverted Pendulum

The rotary inverted pendulum (RIP) is a controls project that has historically been used as a fantastic way to model and test various controller methods. This system consists of a rotary arm that spins around some central base with a pendulum arm pinned to the end of the rotary arm that is capable of rotation about the rotary arm. The system kinematics allow us to determine equations of motion for the RIP, which can be utilized within a controller to vary the torque applied to the rotary arm to generate an angular acceleration (Sukontanak et al., 2009). As the rotary arm undergoes angular acceleration, the now accelerated reference frame of the pendulum arm causes some interesting dynamics to occur, allowing the pendulum arm to seemingly rotate around the end of the rotary arm. As the rotary arm rotates, sensors of some kind can be used to measure how far the rotary arm and pendulum arm have rotated, and this information can then be fed back to the controller, which determines if the pendulum angle is at the desired position, and if not, how much torque should be applied at the next moment in order to get it there.

This loop of the motor being told how much torque to apply by the sensors before the sensors measure the position of the system and then feed that information back to the motor is controlled by the system controller. Within a mechanical system, a controller is, in essence, the part of the overall mechanical system that takes in some input signal or data alongside a reference signal that is desired and determines what type and magnitude of signals the controller needs to output to the rest of the system in order to come closer to that desired input signal.

The goal of my team’s capstone project is to create our own design for a RIP and then create a controller that will allow us to manipulate the system’s responses and actions during three distinct portions of RIP motion for use as a teaching aide in future controls classes taught by Professor Michael Momot. We want our controller to be able to recognize when the RIP is in stable equilibrium so that the system may begin swinging the pendulum arm up to the unstable vertical position under the controller’s guidance. Once the pendulum reaches near the area of pendulum instability, the controller will detect this, and switch it’s algorithms to begin balancing the pendulum instead of swinging it up. Upon switching, the controller will then balance the pendulum in the unstable vertical position indefinitely (Hamza et al., 2019).

This controller has the potential to be created under numerous differing frameworks and models, but the current project plan will see us employing an attempt at a form of a linear time-invariant controller, a proportional, integrated, derivative (PID) controller. We have currently opted to attempt a PID controller as these are generally the most friendly controllers to create, especially when compared to non-linear controllers that require large computation power or other methods like cascade controllers that require an increased amount of processing power from the microcontroller (Boyd, 1991).

This PID controller will take in the position signal of the pendulum arm and rotary arm as well as the desired positions of the arms before computing an error signal which is simply the difference in the two. However, this error signal is constantly fluctuating and experiencing various interferences from things like friction and vibrations within the system. To curb the impacts that these interferences have on the input error signal that is needed to accurately move the system, the error signal is split into three functions of itself and then summed back together to get a more stable error input. The first function is the proportional term, where the original error signal is simply multiplied by some constant called the proportional gain. The second function is the integral term, where the original error signal is integrated with respect to time and then multiplied by a constant known as the integral gain. Finally, the original error signal is differentiated with respect to time and yet again multiplied by some constant, the derivative gain. All three of these gains are normally determined through experimentation or based on desired system output parameters. The summation of all three of these PID terms is then output by the controller, and into the rest of the system to determine what torque needs to be applied by the motor (J Crowe et al., 2005).

This controller will function as a teaching aide for future UVA controls classes as it will be made to be easily modified in order to create differing system responses and response times. This controller should allow students to better understand what the portions of a PID controller actually do and how they are used in engineering applications.

Somewhere around 90% of modern robotic systems employ some form of a PID controller, as it is a relatively simple controller framework. These controllers are allowing robotic systems to take in information from their surroundings and then modify the actions that they take accordingly with no further operator input. This is allowing heavier loads to be moved, more precise motions to be controlled, and overall allowing people and industries to achieve things that were previously unattainable (Nise, 2019). Creating controllers like this can be linked to the modern advances in automation, who’s effects form the foundation of my sociotechnical problem statement.

The Effect of Automation on Unemployment and Job Diversity

My research question is on the impact that automation has on unemployment rates and job diversity in automated industries. A more specific question that is attached to my overall topic that I am interested in researching is the type and quantity of jobs that are created within an industry when that industry experiences large-scale automation that may destroy some jobs.

It is estimated that the introduction of some robotic system into a workplace eliminates 6 jobs from that area (Brown, 2020). On the flip side of this, automation has been seen to increase productivity and efficiency, improving profits for companies and generally increasing economic health in the areas that are automated. These seemingly inverse effects are extremely difficult to diagnose as solely being related to automation (Rotman, 2013). As this happens worker wages are expected to increase. Also, this economic boom in a small area has the potential to create jobs due to industry expansion as well as the necessity of new jobs handling, maintaining, and otherwise keeping tabs on the newly implemented automated systems.

I am interested to see a multitude of things about employment within recently automated fields. Namely, I am interested to see if automation is generally linked to any change in unemployment within affected industries. Also, I want to see if automating an industry has been seen to disproportionately affect different skill levels of workers. For instance, I am curious to see if the jobs that are created when a field is automated require a different skill set or education level than the jobs that are destroyed. If this is the case, even if more jobs are created than are destroyed the workers that were originally displaced by the effects of automation will still likely struggle to find new employment as they are unqualified to fill the created positions (Dizikes, n.d.).

In my analysis of this problem, I will be collecting data in three distinct ways. Firstly, I will be checking over similar papers and surveys to determine unemployment statistics, worker wages, and other economic data that has been collected in the past during times of heavy automation, like the 1920's. This data will be used to create a general picture of the effects that automation is known to have in a vacuum, before being extrapolated into a predictive model as was done in “Automations Impacts on China’s Job Market”, which suggests that if automation is to continue in China, entire cities would become entirely specialized in either automated fields like manufacturing and textiles or they would become solely focused on fields that are not able to be automated. There would be no overlap between industries in the same city (Chen et al., 2021).

Secondly, I will be looking at mathematical projection models of economic health and unemployment across various industries under varying degrees of automation. I will compare this data with the historic data to determine if these projections are somewhat feasible, and then extrapolate this projected data into discussions on what the projections would mean for the health of modern affected workers in the near future. In one such model, it was predicted based off of historical wage and automation data that increasing automation levels across industries would end up decreasing worker wages as skilled workers could more easily be replaced with machines, making their skills less valuable (Arnoud, 2018).

Finally, I will be looking specifically at the relevance and effectiveness of displaced worker training programs in these impacted industries to see if such programs are required to prevent workers from getting entirely displaced from their jobs during automation of their jobs. Additionally, I want to use this data to see if these programs are working as intended and frequently being used within corporations, or if they are ineffective, or not employed due to costs on the company’s part.

Conclusion

The end goal of my technical research is to research and fully create a working rotary inverted pendulum with a functional PID controller. This RIP will be capable of balancing it’s pendulum arm above it’s axis of rotation indefinitely. Also, the RIP will be capable of allowing modifications to the system in order to view differing system responses. If possible within the given time frame, the RIP will also be able to move the balancing pendulum arm to any desired angle around the rotary arm axis of rotation. For my STS research of the effects of automation on unemployment and job diversity, the end goal will be to better understand automation and the effects and ramifications of these processes that may need to be addressed in the coming future. Ideally, I hope to find better guidelines for what parameters and programs are required in order to allow for automation to be healthy for individual workers, companies, and the economy as a whole. Hopefully, predictive models and current and past economic data can shed light on the individual interactions that workers, systems, programs, and employers have with each other that can allow for policies, rules, and healthy practices to be created and better enforced to maximize economic and worker health. I expect that my research will suggest that automation can lead to incredible economic and scientific growth in the coming future so long as ethical consumption, workplace training programs, and access to education are increased accordingly to mitigate lower skilled workers potentially becoming obsolete in the face of automated processes.

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