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Developing Deep Learning Solutions for Lock Acquisition Report 1

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1 Introduction

This project's primary goal is to investigate and develop deep learning techniques to approach the problem of LIGO's lock acquisition. Specifically, we will look into leveraging modern techniques in attention-based learning to help estimate the state of the mirrors given optical signals from the Power Recycled Michelson configuration (PRMI). We will also look into the usage of deep reinforcement techniques in controlling the mirrors directly.

In this interim paper, we report the first $\frac{1}{3}$ of the project in progress. During the first 3 weeks of active research, we first replicated previous deep learning approaches using gated recurrent units (GRU). Secondly, we developed an attention-based state estimator using a transformer architecture. Thirdly, we conceptualized a velocity-position uncertainty estimator in an attempt to use sensor fusion techniques to reconstruct the state of the mirrors. Furthermore, we ruled that the Encoder-Decoder model should be explored only when a working model has been established. Lastly, we implemented a Deep Deterministic Gradient Policy (DDPG) model for a reinforcement learning approach. We report that all three approaches have yet to be thoroughly tested but have now been built. We remain inconclusive but hopeful as to the success of the three techniques.

2 Problem Statement

There are two approaches to acquiring the lock for a given set of mirrors at LIGO. The safe approach is to learn an estimate of the state of the mirrors and the ambitious approach is to learn the controls directly to drive the motions close to 0. The first approach is considered sufficient since if we know the state of the mirrors, it is relatively easy to build these controllers. This is considered safer because the model only suggests additional information to the controllers, furthermore, it is more interpretable than the latter approach. The second approach removes any trace of interpretability and requires one to have faith in the model that it can do what it is set out to do and not break in production.

2.1 The State-Estimator Problem

We revisit the central issue in the state-estimator problem. What we want is, given a set of optical signals, we want to get out the relative positions of the mirrors. The problem is that there exists an infinite number of solutions where these positions satisfy the optical signals we inputted to the model. This is generally not a problem, any solution would work. The issue is, once a solution is chosen, we need to follow that solution over time to preserve the continuity of these trajectories. To simplify the nonuniqueness of the problem, we can "wrap" the data to force the labels to have unique solutions during training.

To perform this wrapping technique we first need to understand the system we're working with. Recall that the PRCL and MICH are *sets of mirrors* and together form a system highlighted in

$$
\begin{aligned}
\phi_{MICH} &= k\delta L_{MICH} \pm \frac{\Omega}{c} L_{MICH} \\
\phi_{PRC} &= k\delta L_{PRC} \pm \frac{\Omega}{c} L_{PRC}
\end{aligned}
\qquad
\begin{aligned}
r_{MICH} &= r_X t_{BS}^2 e^{i\phi_{MICH}} + r_Y r_{BS}^2 e^{-i\phi_{MICH}} \\
t_{MICH} &= t_{BS} r_{BS} \left(r_X e^{i\phi_{MICH}} - r_Y e^{-i\phi_{MICH}} \right) \\
\Psi_{PRC} &= \frac{t_{PR}}{1 - r_{PR} r_{MICH} e^{2i\phi_{PRC}}} \Psi_{IN} \\
\Psi_{REF} &= \frac{i r_{PR} - i t_{PR}^2 r_{MICH} e^{2i\phi_{PRC}}}{1 - r_{PR} r_{MICH} e^{2i\phi_{PRC}}} \Psi_{IN} \\
\Psi_{AP} &= \frac{i t_{MICH} t_{PR} e^{i\phi_{PRC}}}{1 - r_{PR} r_{MICH} e^{2i\phi_{PRC}}} \Psi_{IN}
\end{aligned}
$$

Figure 1: Ψ are the signals we get, however note that there are complex exponentials thus are periodic and is related to L_{MICH} and L_{PRCL}

figure 2. We can numerically recover the signals produced from the length L_{MICH} and L_{PRC} using a set of equations shown in 1. following equations, where k is the wave number and Ω is a constant related to the laser, c is the speed of light:

$$\phi_{MICH} = k\delta L_{MICH} \pm \Omega/c L_{MICH}$$
$$\phi_{PRC} = k\delta L_{PRC} \pm \Omega/c L_{PRC}$$

With enough elbow grease one can reduce the signals Ψ's such that they are related to L_{MICH} and L_{PRCL}. The issue is that leaving it in such a form it is difficult to retrieve the period of the signals analytically since there is a mix of terms with L_{PRC} and L_{MICH}. Thus to simplify this we can apply a linear transformation namely

$$Z_1 = 2(L_{PRCL} + \frac{L_{MICH}}{2})$$
$$Z_2 = 2(L_{PRCL} - \frac{L_{MICH}}{2})$$

If we plug this transformation into the equations we retrieve a period of $/2$. With this transformations we can now wrap the data.

Firstly we will take the PRCL and MICH positions and follow the transformations described for Z1 and Z2. After that is done, we iterate through the data and linearly shift up or shift down by integer multiples of the period such that all positions are restricted between $\lambda/4 \rightarrow -\lambda/4$. Then we transform back returning the PRCL and MICH positions successfully wrapped. This helps guarantee that for every signal the corresponding wrapped position is unique!

This technique is a problem in production. When computing these we have to undo this preprocessing step and unwrap the data in a manner that retains continuity such that the reconstructions

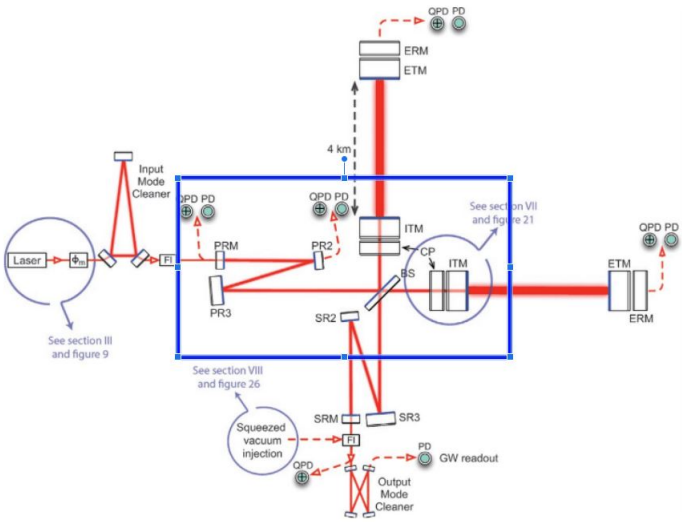

Figure 2: The rectangle boxed section is the PRCL MICH system that we're considering.

are accurate. We need to unwrap the data inorder to recover the true positions. This is what we call the wrapping problem.

3 Baseline Model

Previous attempts in state estimation used gated recurrent units called GRUs [1] [2] to predict the wrapped positions. GRUs are a class of recurrent neural networks. Recurrent neural networks (RNN) are simply neural networks that work with sequential data. They are often written with a recursive definition. A more concrete implementation requires one to pass information from previous time steps to the next. At the first time step, we input data into a classical neural network, then during the next time step, we input both the new data observed and the hidden state from the previous time step and continue until we reach the end of the sequence. Each set of feed forward networks for input data is called a cell or unit. This way we can pass information from previous observations to inform the model in the decision-making process. The classical RNN described suffers from a host of memory issues. With each passing of hidden states, data from the beginning may not be represented well further down the sequence, GRUs take the RNN idea further by developing specific gates within each cell that manipulate the hidden states that are passed down called the reset gate, and update gate[1]. The reset gate can selectively choose to nullify certain data that are passed from before, and the update gate decides what's important to pass on to the next state[2].

This technique was chosen because the data is time series and secondly the input data is relatively long on the order of 1000's input samples. This was the reasoning for this approach back in 2017. To that end, our first task was to replicate these results which we successfully did.

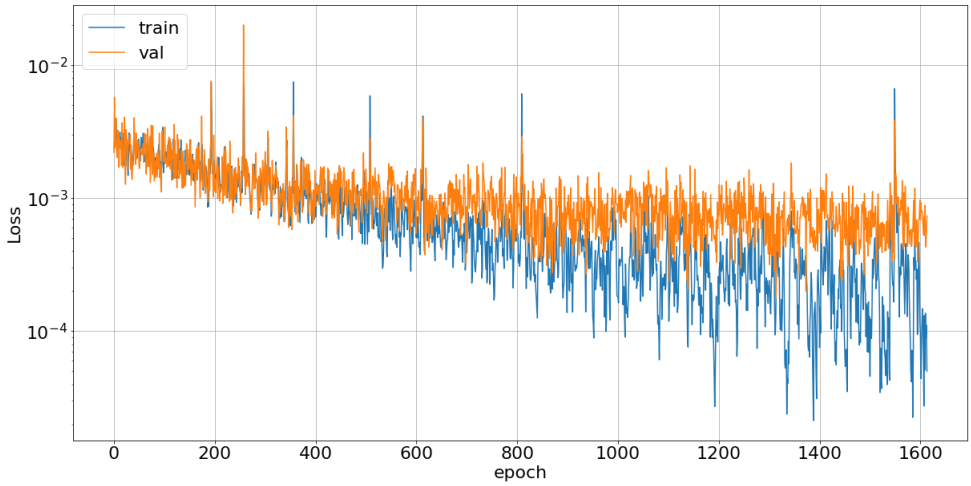

Figure 3: This is the loss curve for the model training.

3.1 Methods

We implemented a GRU in KERAS framework[3]. The data used for training was simulated PRCL and MICH with approximately 40,000 samples each 0.5 seconds long sampled at 2048Hz. Given these optical signals, we then try to recreate a single-time step of position data.

The model architecture had 2 GRU layers, with 128 units each, followed by 4 fully connected layers of 4092, 512, 32, and 2 units respectively. Each layer used a ReLU activation except for the final layer which is given a linear activation. We used the Adaptive moment (AdaM) optimizer with a learning rate of 1e-3. The reconstructions are as follows in the following diagrams [1].

This approach is insufficient because we cannot leave the data wrapped. This is because in reality the mirrors are free to move beyond the range which we restricted the solutions to. Thus to retrieve the true relative motions we must stitch back the reconstructions. Furthermore, these sharp positions are unphysical and is entirely the result of training the model on a training set where we linearly shifted the data down into the range of $\lambda/2 \rightarrow -\lambda/2$ where we know unique solutions exist. However, piecing together these solutions is a surprisingly formidable challenge.

To appreciate the problem, how one would typically approach unwrapping the data is to write a program that iterates through the reconstructions and detect sharp changes in position. Once the discontinuity is found we transform the data into the Z1/Z2 space and linearly adjust by integer multiples of $\lambda/2$ such that the discontinuity is minimized. The way in which we can detect these discontinuities is to look at the derivative as finite differences. The big problem is that neural networks are smooth mappings from input to outputs and in this case the outputs are also relatively smooth thus it makes recovering the original discontinuities difficult see, figure 4. Although it appears to be easy to detect by eye, to detect these sharp changes numerically is harder because numerically because they appear smoother and can be confused with inperfect reconstructions. Thus we're met with the wrapping problem.

[1] Code link

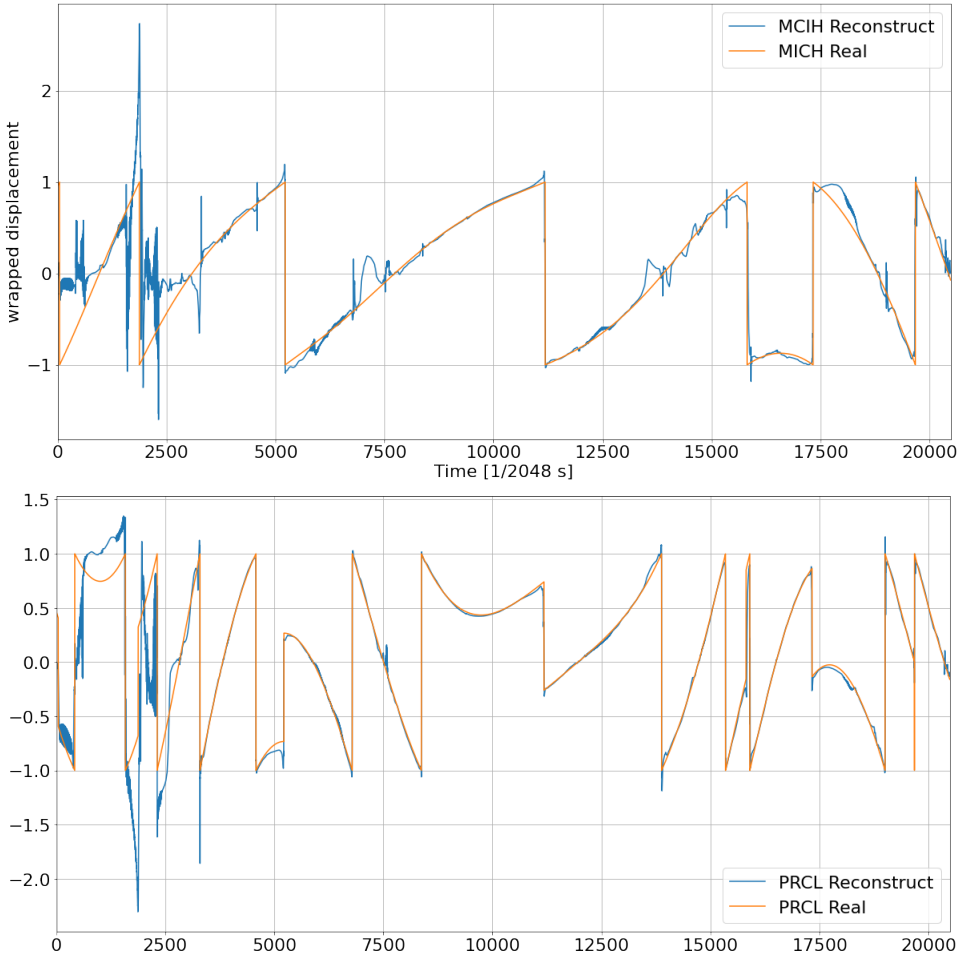

Figure 4: These are the reconstructions for PRCL and MICH.

3.2 Control Problem

4 Attention Based Estimators

Perhaps we can defeat the wrapping problem, by ignoring wrapping problem? We approach the problem with *brute force*. We assume that given sufficient history of signals, we can hope to extract unique solutions for the input signal. The major challenge here is that even the GRU's used in the original implementation still fail to generalize to *very* long sequences of data. The problem of retaining memory of various parts of a long sequence is a well-known shortcoming of recurrent neural networks. Luckily in 2017, a novel approach in the domain of natural language processing sought the advancement of transformers and the use of self-attention which effectively solved this problem[4].

4.1 Self Attention

In principle, attention is an intuitive concept[2]. Traditional attention helps assigns a weight to certain inputs of data as to how important they are to the problem they are trying to solve. In technical terms, we call this a query. However there is an issue with this, we lack context! For example, in the sentence, "I picked up some cash from the bank and went for a swim at the bank of a river" the word bank has 2 different meanings. Humans interpret this by looking at the context. To get machines to do the same is called self-attention. We look at the relationship of the word "bank" with the word "cash" and then we look at the relative attention of the words "bank" and "river" to infer these meanings. We look at the attention relative to words in the sentence itself, hence self-attention. This attention gives context to the data. This effectively defeats the memory problem because the model has no recurrent element! We do not need to engineer a means of holding a single "memory" unit when the model has completely freedom to attend to any input information freely at any point.

Armed with intuition, we build such an algorithm [3][4]. We have three main elements, the KEY, the QUERY, and the VALUE each will be three separate linear layers 5. This is motivated by how retrieval systems work. We have a query, and we find the matching key and return the value. Attention is this search process. We only pay attention to the most similar items that we look for and disregard the rest. This suggests that we want to find the highest amount of similarity with itself as this is self-attention. Hench the KEY and the QUERY will have the same inputs to each linear layer. Concretely one finds similarity by looking at the cosine similarity. This is easily computed via the dot product. To do this with the matrices of the KEY and the QUERY, we simply matrix multiply the outputs of the linear layers. This encodes the ATTENTION FILTER. We then scale this layer and compute the softmax of this filter to arrive at numbers that sum to 1. Then we multiply this with the VALUE, which up until now is just the input passed through a linear

[2]Good video on general attention here
[3]tutorial on transformers KERAS here
[4]Very good Youtube video on self attention here

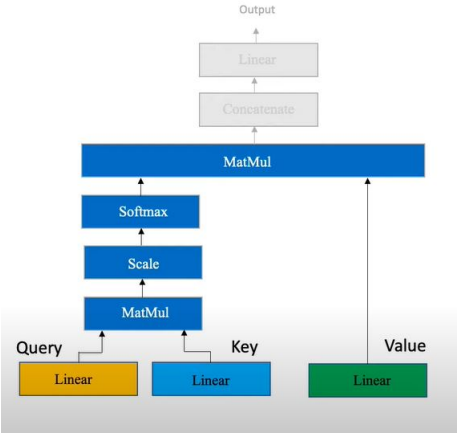

Figure 5: This is a concrete diagram showing the flow of data for self attention.[4]

layer. This matrix of numbers then helps us weigh and select the values from the original input and thus gives us the FILTERED VALUES. This process is called self-attention with a single head. If we want multiheaded self-attention, we repeat the entire process but with multiple layers and concatenate the final results together!

Attention works well, however, there is a key problem, these models don't consider ordering of the data. One of the transformer's great power is that it processes data in parallel instead of sequentially. This means that in the layer for self attention the aggregation is done on its own. More concretely, the attention values will always be the same no matter the order in which they appear. If we think about it, all the attention mechanism is doing is computing a weighted scalar between any pair of data in the sequence this scalar is created with 0 information about positions. However this would be a problem because in reality we know position affects how much attention is given to each data point. Thus before the transformer step we need to encode the positions, footnote Good video on positional embeddings here.

To fix this, we apply a positional embedding of the input, whereby we take the embedded data (in NLP terms means converting text to vectors) we learn an embedding by adding vectors to the embedded word vector. This small offset helps encode information about the positional information of the vector WITHOUT changing the contextual representation of the input. For example, the appearance of the word "Queen" as the second word in the sentence should appear nearby in the vector space from other appearances of the word "Queen" but they all should nonetheless be slightly different from each other depending on where in the sentence they appear. However, they can't be so far apart such that the word "QUEEN" appears to be an entirely different world altogether! These "offsets" are what is learned by positional embeddings.

Here we arrive at the second major issue, positional embeddings work well for language tasks, however, general time series data are not words. NLP tasks involve discrete chunks of inputs, that are finite, for generic time series problems, we don't have that luxury as data is continuous and infinite. Hence positional embeddings become a problem. The solution involves representation learning with an algorithm called the TIME2VEC embedding technique[5] [5].

[5]Good Blog post on implementation of time2vec here

4.2 TIME2VEC

Time to vector is an attempt to embed temporal information in time-series data. Firstly there are 2 major requirements for this embedding[5].

1. Embedded data should be invariant to time rescaling. In other words, if the data were taken at increments of 1 day or 2 months, or 3 picoseconds it shouldn't affect how the data appears in the end. 2. Representations of time should both capture periodic patterns and nonperiodic patterns [5].

To satisfy these constraints we (of course very naturally) arrive at the following formulations[5]. The i is the index of the number of kernels, τ is the timeseries data itself. The w_i, φ_i are the learned parameters in which the

$$\mathbf{t2v}(\tau)[i] = \begin{cases} w_i\tau + \varphi_i, \text{if} i = 0, \\ \mathcal{F}(w_i\tau + \varphi_i), \text{if} 1 \leq i \leq k \end{cases} \tag{1}$$

I have yet to truly appreciate the mathematics of why this works but, concretely the first element represents the linear behaviors of the data and the second represents the periodic behaviors of the data where $\mathcal{F}$ is described as the a periodic activation function. Read more here [5].

Armed with these new techniques, we approach defeating the wrapping problem.

4.3 Results Stage 1

In stage 1, we want to first and foremost, ensure that we can at least replicate the performance of the GRU on wrapped data with the transformers. We implemented the following model:

Time2Vec embedding Layer [no hyperparams]

3 X Transformer Blocks [embed dim = 12, fully connected encoder =1024 , num heads=8]

4x Fully Connected [RELU, dims= 4096, 512, 32, 1]

Transformers can be difficult to train, as such we need a custom "warm-up" section whereby the learning rate is low but grows exponentially to the initialized learning rate. The warmup learning rate is 1e-6 and the final learning rate is 1-3 and the warmup time is 500 epochs[6].

Note: we were only able to achieve comparable performance with the GRU models if we trained separate neural networks for the PRCL and the MICH data. Why? Not sure why at the moment... Will figure it out later.

[6] code here

4.4 Stage 2

In stage 2, we take the model from the first setup and we extend this to the problem with unwrapped positions. This has been implemented but not yet executed. Spent the entire time building the baseline Attention Model first.

We will benchmark this against the baseline model on the SAME unwrapped data.

4.5 Success or Failure?

Success would be an accurate reconstruction of positions with respect to the test dataset with an MSE on the same order of magnitude as the wrapped GRU results. Failure is when even given a high number of model parameters, the attention-based model's reconstruction is no better than the GRU trained on the same dataset. This helps us conclude that the wrapping problem is not necessarily a memory issue, but is most likely intrinsic to the data itself. Suggesting the approach is potentially flawed.

5 Velocity Position Uncertainty Estimate

Having approached the problem with brute force as with attention, we concurrently investigate more elegant means of reconstructing the positions. In this approach, we accept our doomed fate and wrap the positions of the estimator. The trick is, that we know that the velocity of the mirrors is unique. Given this information, we attempt to recreate both the velocity and the position of the data. Together we can attempt to fuse these two data points together to reconstruct the accurate positions.

To build intuition, for a given position, the next forward position will have an infinite number of solutions. With the knowledge of the velocity estimate, we can use that to select a position (out of the infinite solutions) such that the new velocity has the least uncertainty. To accomplish this task we can use the Kalman Filter [6] to do such magic. Thus we reduced the problem to: "can we build neural networks that can predict the inherent uncertainty in the prediction".

There are 2 natural ways of approaching the problem:

5.1 Method 1

Probabilistic Models. We take inspiration from Variational Autoencoders[7]. Consider a classical feed-forward neural network for a regression problem. Now consider that the last layer splits into two layers which we denote as the mean and the other as the log variance. Then when optimizing

the model, we compute the probability that the target appears in our predicted probability distribution. Intuitively this makes sense in capturing the error of the estimator. If the model was inherently poor at making predictions, the variance should be high, this way there is a higher random chance that the model predicts the correct solution. However, if the model is highly accurate, then the variance should drop, or else there is a higher random chance it predicts data points far away from the target. Thus in theory as the model improves, the variance should drop and the mean should approach the target value. The PDF we chose is a Guassian given by:

$$P(y|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{1}{2\sigma^2}(-(y-\mu)^2)} \tag{2}$$

5.1.1 Results

We have finished implementing this idea. However, the model struggles to learn what we want it to learn. More debugging awaits. It is entirely possible that this approach is unfavorable.[7]

5.2 Method 2

In the second method, we build an entirely new model whose purpose is to predict the square of the errors made by the estimator. Intuitively this could also work, given enough data samples, the model experiences examples that are similar in nature which would correspond to performing a series of similar measurements.[8]

5.2.1 Results

TBD

6 Deep Deterministic Policy Gradient

6.1 Motivation

Generally speaking, some of the greatest advances in machine learning come from increasingly abstracting away tasks and simply letting the machine do everything. This has loosely been the trend in ML research for a number of years. Back in the 'prehistoric eras', ML models used to work only with highly hand-crafted features for input, that was until the advent of deep learning

[7] code: here
[8] code here

when we saw these features learned implicitly by our algorithms. We increasingly try to move the human further away from the picture and surprisingly found huge improvements from computer vision tasks to all the way to NLP. This similar philosophy is adopted by some of the most successful ML researchers tackling various kinds of hard problem. Quoting Deepmind's CEO Demis Hassabis, "let the gradients run through everything". We approach hard problems initially with an intermediate solution that often requires lots of hand-tuning, to which then practitioners try to generalize the approach to the bigger problem. We saw this with the invention of the CNN, we saw this with the invention of Alphafold1 $\rightarrow$ Alphafold2[8], we saw this with the invention of transformers, and we will probably continue to see this trend until either we create the Terminator and kneel before our AI overlords, or figure out some other way to solve intelligence. This is scary because we lack agency, but time and time again we've been proven wrong, in a good way. This possible upside in "superhuman" abilities alone is enough to warrant at least an investigation into its potential. Because of this, despite my supervisor's skepticism in letting me build an AI to control LIGO mirrors directly, I wanted to approach this problem in the most general way possible which is directly learning the controls of these mirrors.

More concretely, RL could be interesting because we know that giving only the information about the signals might not be enough to recreate the positions. What might hint that RL can solve the problem is that we can provide models with additional information, specifically the reward signal at certain time steps. The optical signals received plus the expected reward for certain actions could help us gauge what kinds of controls engage. This could provide unique solutions to the control problem. However, this is not trivially clear that this is the case and further investigation is needed. I briefly diverted some time on this problem.

6.2 DDPG Method

In classical approaches to reinforcement learning, we typically use tabular methods. These algorithms work by searching a space of actions and storing these optimal actions at a given state in Q tables. These tables help inform how to perform tasks given the state you're at. Typically these solutions could involve dynamic programming, temporal difference learning, or Monte Carlo tree searches. These methods are only tractable when the state space is finite. However, in most practical cases these state spaces are near-infinite. For this, we need approximate solution methods. A well-known means of approximation is to use neural networks such as Deep Q learning [9]. Given some arbitrary continuous state, we can predict the expected reward value for a particular action, this is the q function in RL terms. However, neural networks have a finite number of predictions, thus this method also relies on the fact that the action space itself is finite. What happens when the action space is also infinite? Just like how we used a neural network to predict the action's value we use a second neural network to then evaluate the network's performance in an ACTOR and CRITIC setup. Similar to a generator and a discriminator in GANs for computer vision, the actor, given the input produces actions that are continuous values. Then we have a critic that takes in the state, and the predicted actions and tries to predict the expected discounted reward on that action taken. This allows an agent to maneuver and learn from a continuous state space and action space which is important in our setup.

To use this technique we have numerical simulations that provide actions based on the continuous state of the optical signals. We also want to predict continuous actions and direct how much force each of the servos should engage to drive down the motions. Thus the first RL approach we should take would be DDPG methods[9] [10].

6.3 Reward Function

Reward function or the reward signal is the objective of the problem. On each timestep the environment sends the agent a single number and the goal is to maximize this reward over a long term period. We know our goal is to push the mirrors into a linear regime. We can detect this linear regime by looking at the signal responses specifically POP. When the power of the optical signals shown by POP is high and constant, then we will know we can easily acquire the lock. To mathematically formulate this, we craft a reward function which is the inverse square of the derivative of the power. This way, when the change is constant we get maximal reward whereas any large change won't receive any. We square it to make the reward invariant to the sign of the derivative. We add an ε term to make this numerically stable. We also have a step function for the reward. Given high power, we reward the model for achieving such. S_t is the state received from the environment i.e the signals at time t. We set some *const* as the threshold for when we consider it to be high enough power. We set α as a constant hyperparameter in scaling the rewards.

$$R_t = \begin{cases} [(\frac{dS_t}{dt})^2 + \varepsilon]^{-1} + \alpha & \text{if } S_t > const \\ -\alpha, & \text{else} \end{cases} \tag{3}$$

6.4 Results

TBD

7 Forward

In the first 3 weeks of the project, we have finished implementing nearly all the algorithms we hope to investigate. We have implemented baseline models, attention-based estimators, velocity-position uncertainty estimators, and DDPG models. We currently plan to dedicate the rest of the time to tuning and investigating if these implementations work.

[9] code: here

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