I. Cover Page

Pillbot

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Final 1-Min Video: https://youtu.be/R3rbF5QIQhU

10-Min Overview Video: https://youtu.be/Bu_waBqKh-U

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II. Executive Summary

Pillbot is a Smart IOT Health Tech startup centered around increasing patient prescription adherence. This is done through a combination of a handheld pill dispenser and online data platform that allows for opt-in sharing of patient data with doctors so that treatments may be tailored best to fit individual needs. Current solutions are lacking either in terms of granular data collection that is pertinent to aiding doctor recommendations or are so cumbersome to use that patients will avoid them altogether. We strive to center our design around the end user, using a human systems approach, so that they are as likely to adopt PillBot into their daily routine as possible. The merit of which comes from the severe gap that currently exists between drug prescriptions and patient outcomes. By collecting this data as an opt-in feature and delivering it only to doctors and loved ones, if wanted, Pillbot addresses the current medicine adherence problem at the root of the problem.

In aim of this goal, a fully functioning prototype of the PillBot device was created, both with and without IOT components to best serve the needs of different users, namely first time opioid patients and clinical trial participants. The device visually alerts users when it is time to take their medication, and upon button request, dispenses the proper dosage for them while tracking the data from each interaction. In combination with the physical device is our online data web platform that has been designed from the ground up to take in patient adherence data and predict future trends using an AI algorithm that has been pre-trained on comparable data sets.

III. Overview and motivation of the Project

Currently in America, over 200 million opioid prescriptions are written each and every year, leading to over 90 thousand deaths annually from opioid overdose. This stems from a lack of patient adherence in which up to 50% of patients are non-adherent to their prescription regiments, costing the healthcare industry $280 billion annually.

This patient non-adherence is caused by two primary factors. First, patients are given medication in the standard pill bottle where there is no barrier to taking more than prescribed at any given time. Once the bottle is open, there is nothing about the bottle that works to curb the patient's impulse. This existing lack of impulse control on the delivery end is only compounded by the fact that doctors have no insight into patient behavior trends when taking medication, aside from the patient’s own verbal account which may be unintentionally erroneous or incomplete. Thus, doctors are unable to properly assess patient symptoms, outcomes, and results from the prescribed treatment. This lack of information leads to subpar recommendations going forward as the efficacy of and adherence to prior treatments must be inferred.

While the primary medication container is the standard pill bottle, there are several existing alternatives that offer some kind of smart features to achieve better health outcomes. However, they each have their own limitations and drawbacks. The largest of these common shortcomings is that the majority of third party pill dispensers are given to patients in a B2C fashion meaning that they themselves must seek them out, finance the cost, and handle the logistics of setting up and maintaining the device.

These alternatives fall into four main categories: handheld adherence trackers, large countertop style pill dispensers, mini pill organizers, and special packaging solutions.

First, special packaging solutions do clearly exhibit to the patient what medications should be taken at a time. However, without any form of electronic component, their offering ends there as loved ones and caregivers are never given any window into whether or not the medications inside were taken at the appropriate time. Furthermore, patients still have essentially no barrier to taking more than they are alloted at any given time. An example of this solution is Pillpack.

Pill organizers that incorporate an IOT component are a logical next step in adherence tracking from special packaging. However again, they too have some limitations. While they can detect when the lid to the device is opened, this is not enough information to detect how many pills were taken at any given time or even which pills were taken, depending on model. Furthermore, these devices are often too large to be easily transported. Examples of this are Elliegrid and Medminder.

Large countertop dispensers do solve problems with granular adherence tracking as they directly give patients the exact dosage that they are prescribed and can alert doctors or loved ones if there is a deviation in the taking of said medication, but they do so with major compromises to a patient's workflow. The machines must remain stationary and plugged into a wall outlet, meaning that a patient cannot take medication from these devices while receiving the benefits that they offer from outside of their house. Furthermore, these dispensers are quite loud due to the mechanisms used inside and have extremely predatory pricing structures that cost patients hundreds of dollars each year. Examples of this are Hero and Medacube.

Lastly are handheld adherence trackers. These devices are most similar to PillBot in terms of goal, but have some key limitations. First, the devices do not collect granular, pill count specific, data when patients open the lid to take pills (there are versions of these devices that do, but when this feature is present, a much larger form factor is taken). Furthermore, since the mechanism is still just a single lid, there is nothing present resisting the urge to overtake.

With no current solutions being able to fully tackle the ongoing problem of non-adherence from a granular tracking, impulse curving, and doctor informing standpoint, there is clearly a gap for a new solution that can ultimately lead to the saving of thousands of lives and billions of dollars each year.

The objective of this project then is to develop an ecosystem that addresses non-adherence at the source by giving patients their medication in a way that does not heavily impede their current workflow but also encourages them to make healthy choices, all while alerting their doctors and loved ones of any worrying trends should they wish.

IV. **Technical Description**

A. Specifications and Requirements

Entering into senior design, the team had some ideas for the specifications of the overall solution. These Preliminary specifications for PillBot to be successful were a combination of a physical device and web platform that would allow for medication adherence tracking and analytics by AI and doctors remotely. To accomplish the physical end, some design factors were for the device to be compact, capable of carrying a full prescription's worth of medication, and for the device to be portable with some kind of electronic dispensing component.

At the beginning of senior design, we entered with an in-progress version of the physical device that, when finished, would meet these specifications. Specifically, it could house a full 90-days worth of medication for average pill sizes, had a rechargeable battery so that it could last the full length of a prescription, and had a PCB to handle dispensing through our motor and internal mechanics. However, after bringing this version to fruition and acquiring feedback during the fall, we reached the conclusion that the device, while still being the size of a larger pill bottle, was still too large and not ergonomically friendly. As a result, we pivoted the external design of the device to be more compact and friendly to hold and transport. We then targeted a size that someone could operate with one hand and fit in their pocket.

During the fall semester, we also interviewed several key stakeholders including insurance representatives, doctors, and investors to receive feedback on primarily the business facing aspect of PillBot. From these interviews we concluded that for PillBot to actually gain traction, the device would have to be as simple and cost effective as possible for insurance companies to actually be willing to subsidize it. As a result, we targeted a total cost of goods sold to be under ten dollars per device. In aim of this goal and to minimize complexity, we decided to forgo rechargeability on the device and to hold off on any internet connected components. To achieve this goal, the device's battery length was now targeted at 5 days, the length of a typical opioid prescription, so that a primary cell could be used to power the device and so that users would not have to recharge it.

When later moving to develop an IOT version of the device, there were several parameters that had to be reconsidered. Firstly, battery length could be reduced to a single day with the expectation of a user to recharge the device. Secondly, the bill of materials could be increased as the use case of this device, clinical trials, would be more lenient in this regard than insurance companies. The same form factor was targeted though in order to maintain usability and interest.

On top of these monetary and physical restrictions, there are also FDA regulations that PillBot must comply with. Specifically, PillBot was designed to meet Class 1 certification and 510k exemption under the precedent of physical medication dispensers. This specific category would mean a streamlined process for PillBot to gain regulatory approval both in terms of time, 2-3 months rather than years, and cost. To meet these criteria, PillBot must be designed to never stop users from actually accessing their medication and still allow access in a manner that is deemed child safe, requiring at least two distinct actions to reach medication.

On the software side, PillBot first required a secure, cost-effective, and scalable method of data storage. Given the sensitive nature of collected patient data, in order to be compliant with data standards, our storage method was designed to prioritize the protection of data. Additionally, while the amount of patient data collected will grow significantly as PillBot is used, we sought to avoid allocating too much unused initial memory to save costs. Finally, we required a method that would allow us to access this data with low latency (under 50 ms) for analytical purposes and to be displayed on the frontend of our doctor facing website.

B. Iterations:

PillBot went through three main iterations over the course of senior design.
First in fall, the team completed its first fully working MVP. This version of the device was a work in progress entering into senior design and had its core electronics and mechanical housing

developed, but was not functioning reliably. This version was designed around an ability to dispense pills on a 90 day supply of pills and thus had an ability to recharge and enough capacity for this duration.

After completing this version of the device and receiving feedback, the team decided to pivot towards a more streamlined, simple, and cost practical form of the device. This is where the smaller form factor and lessened BOM stemmed from at the end of Senior Design Fall in December. The key feedback leading to these decisions were interviews with our key stakeholders, namely individuals who were associated with the healthcare space on the insurance and pharmacy benefit side, who indicated that the existing device was too expensive and too complex from a willingness to adopt and reimbursement standpoints. In addition to these monetary stakeholders, doctors, and potential patients all stated that the device was too large and un-ergonomic to be actually adopted by patients into their workflow. We discussed this with our advisor James Won about what possible use cases and design features we should be taking into account when modeling the new enclosure including hand placement, sizing, and departures from existing workflows. From here, a simpler, smaller version of PillBot was developed over the first portion of Senior Design Spring.

However, after hearing feedback on this version of the device, the team also decided to design an alternative version of the device that utilized IOT. This was done for two primary reasons. First, the existing version did not lend itself well to clinical trials and measuring efficacy on a daily basis. While it was designed to be effective on a mass scale, actual studies that could use the device would be offered little in return for using PillBot. Thus, an always connected version of the device was created that would give clinicians real time access to patient behavior trends and adherence analytics updates. The second primary factor for these design decisions was after discussing current competitive alternatives, the team decided to develop this version of the device to fully address all aspects of the existing market that were not currently met by PillBot.

With respect to data analytics, several iterations of both the UI and algorithms were developed. Our doctor-facing web platform was designed after surveying several care providers to be optimized for their needs, and easily integrate into their current workflow. As a human systems expert, our advisor, Dr. James Won, provided additional feedback regarding the resulting UI developed by the middle of the semester, emphasizing ease of access to the most important information for care providers, from page navigation to color coordination.

C. *Societal, Environments, or economic considerations:*

PillBot has several considerations to be made in regards to these three categories. First from a societal perspective is the problem that PillBot seeks to tackle. Medicine non-adherence is a critical problem in the existing healthcare industry costing thousands of people their lives each year and the healthcare industry billions of dollars annually. As an entry point, PillBot has primarily been designed for opioid use. After surveying potential patients, it was concluded that the root of this problem stems from a lack of barriers to patients becoming addicted in the first place, both from a dispensing standpoint and from a doctoral standpoint. Currently, patients are only limited by the number of pills present in a standard pill bottle after the lid is opened. Furthermore, doctors are completely left in the dark when trying to interpret, predict, and advise patient outcomes when trying to gauge how their medication has been taken and what repercussions may arise. Thus, PillBot has been designed to curve a patient's impulse when seeking to take additional medication, while still allowing them to, all while collecting their usage patterns for doctors to best help them later on if they opt into it. This leads into the more nuanced social consideration that PillBot must make, ensuring that patients are not penalized or stigmatized for trying to access the best health treatments possible. In aim of this goal, PillBot has been designed to be discrete on the level of a standard pill bottle, capable of being fit in a bag easily, and ensuring that patients have no fear from the predatory healthcare industry by only sharing anonymous bulk data with insurance companies and only sharing personalized data with doctors and loved ones on an opt-in basis.

From an environmental standpoint, PillBot seeks to minimize waste as much as possible. In pursuit of this goal, all components are created with recycling in mind. While not done in the current prototypes due to the methods currently accessible, PillBot at scale will be created from injection molded plastic that is fully recyclable. Additionally, all electronic components other than the button, specifically the motor and PCB, are housed separately from medication and patients so they may be removed and reused into new PillBot devices to minimize E-waste.

Lastly from an economics standpoint, PillBot has been cost optimized through a simplified BOM and reduction in complex plastic parts to make the current costs as enticing to reimburses as possible. Furthermore, in order to ensure that no financial burden is placed on patients for seeking better treatment, all costs are paid for entirely by insurance companies or hospitals in a B2B fashion.

D. Technical description and approach:

From a technical standpoint, the physical PillBot device was designed to solve the problem of medicine tracking adherence. To do so, a few key sub-components were determined early on to be used inside of the device in order to achieve full functionality. These include a button to register dispense requests, a motor to actually dispense the medication, an IR sensor that would detect when a pill had been dispensed, a battery to power the device, and a microcontroller to actually perform and log the dispensing.

In the non-IOT version of the device begun in Fall and finished in Spring Senior Design, deemed PillBot Core, this was all accomplished using custom solutions from the mechanics to the PCB. This was primarily done to ensure that all components fit within the desired form factor of the device. Specifically, the PCB, battery, and dispensing mechanism had to all fit within a diameter of 1 inch to ensure that the final device was portable and ergonomic enough for patients to be willing to use it. The custom PCB in this version ran off of an ATTiny 85 microcontroller. While other versions of the PCB were designed that involved more complex microcontrollers like the SAMD, the Tiny was chosen as it was small, capable of being soldered by hand, relatively power efficient for our use case, easily programmed, and most importantly available during the recent chip shortage. The PCB itself was designed in Altium Designer (See Appendices B-D) and was manufactured by Advanced PCB, later being soldered by hand by the team. The PCB has numerous connections for which external components can be mounted, specifically for the infrared sensor which would have to be placed lower in the device and button that users would interact with (The mosfet was mounted this way while assembling). On board however (See Appendix E) are filtering capacitors to ensure a smooth voltage supply, an nmos transistor to control flow of current through the motor when dispensing, a reset button primarily used when debugging and uploading code, and an LED to indicate when it was time to dispense. Vias on the PCB were deliberately made to be un-tented in order to preserve points where wires could be connected in the event of debugging or assembly needs that warranted these connections, something that was integral to our successful assembly by demo day as we used primarily off-board components in this construction due to speed and availability (See Appendix M). USB terminating resistors were placed on the communication lines so that serial communication could occur over pins three and four which in a finalized version would allow for connections through an onboard microUSB (When testing a split USB cable was used to connect to soldered pins). This aspect of the device was still a work in progress and required an intermediary device when writing code and reading results, namely the Arduino Uno acting as ISP. After being programmed though, the device could function on its own, controlling the motor and reading button presses. Assigning of pins was done in a way that would optimize pins as pin four also would control voltage to the motor, but this would not cause an issue when trying to read from the device as the motor is only on when the button is pressed. When actually uploading code to the device, an Arduino Uno is used as an in system programmer. This method of connection and writing to the PCB was successful and was capable of uploading a working program to the ATTiny. Power for this device was also a major concern. The ATTiny85 draws about 8mA of current which from a 1AH CR2477 would lead to 125 hours of operation, or 5 days which was our target length. The motor was powered through its own coin cell battery as it would pull an average of 50mA when dispensing. At an average dispensing time of 2 seconds and an average dispensing count of twice per day, this would allow for 5 days of use as well. It should be noted that these coin cells are within the diameter of the PCB and are smaller than the internal cavity of the device so that they would fit easily within the device.

When pivoting towards the IOT version, deemed PillBot Plus, the device was constructed entirely of off the shelf parts and assembled externally from the device due to the lack of time to have a new IOT PCB shipped and assembled. To allow for internet connectivity, an ESP32 microcontroller was chosen as it provides the ability to connect over Wi-Fi 2.4GHz and over bluetooth. Furthermore, this microcontroller was ideal as it provided external battery recharge capabilities by default. When using this new board, circuitry setup was essentially the same as the non-IOT version with a mosfet being used to control motor activity, a button for acknowledging dispenses, and an LED for indication. In terms of software, the device leveraged existing documentation on AWS IOT cloud platform implementations to use an MQTT broker communication with the PillBot AWS platform. This skeleton was a useful starting point but had several omissions that had to be overcome. This code was tested by sending test dispenses.

Mechanically, the two versions of the device function the same with an internal tray like piece that houses the rotating disk and chute that actually catches and dispenses the pills (See Appendix N). This piece is connected to our motor via a gear in a 1:1 ratio primarily done to prevent slipping and because torque and speed requirements are both quite low. All of these structures were printed using both SLA and resin printing, but different pieces showed better results for each method. The external housing clearly favored the resin printer as it was smooth in the hand and more visually appealing without the presence of SLA artifacts such as layer lines. The internal gears and dispensing mechanism however performed better when printed via SLA due to the higher precision in printing and the higher coefficient of friction of the resin prints on smooth surfaces due to the material. The resin printer likely could have outperformed the

SLA in regards to precision though if the machine was tuned over the course of several months and hundreds of prints. The resin printer was certainly key though in experimentation with external form factors and even preliminary trials as it could create parts in higher volume faster. This is because SLA speed varies by mass whereas resin varies by object height. 3D enclosure designs were done to conform to the average human hand size such that the button was easily accessible while holding the device with a single hand. Also, the sliding cap and button press combination was done to conform with FDA two step requirements. In terms of patient use of the device, they can visually see the indicator light flash, slide open the lid, press the button, and catch the pill being dispensed with their free hand. If they wish to take medication outside of their prescribed schedule, they simply hold the button for 30 seconds to dispense. This functionality was tested by running pills through the device while in hand at a variety of angles.

With respect to the machine learning algorithms, we sought to predict future patient adherence using past patient behavior. To begin doing so, the first step of the process involved data collection; however, as the granular adherence data that PillBot collects is not currently available, we were forced to search for substitutes. We initially attempted to train our model on marketing purchase data, available in bulk form; a patient purchasing an item in a given period was assumed to be analogous to a patient adhering to their medication. This binary data was used to output a probability of purchase or adherence in the next period given behavior over prior periods. As we were able to test our device and collect more data over time, towards the end of the semester, we were able to switch daily binary patient adherence indicators as a better substitute.

We then trained a variety of different models on this data. We firstly tried the Pareto/NBD model, a new marketing model proposed by Dr. Peter Fader of Penn's marketing department. This model utilizes a Gamma mixture of poisson distributions to analyze patient adherence and deviations from prescriptions. While this model performed well on the initial marketing dataset, its performance predictably fell off once we switched to actual patient adherence data. We additionally utilized CNNs, convolutional neural networks, and random forests, which displayed a nearly 80% accuracy in their predictions. However, we ended up using a simple linear regression, which displayed about 73% accuracy, due to its simplicity and interpretability as a model, but also for its computational speed. While the random forest and CNN required loading a large model in the backend, requiring high initialization times, the regression model could be computed directly in the frontend with ease. Thus, this algorithm could be directly integrated into the AWS workflow we used for the web platform, utilizing S3, Cognito, and Dynamo DB. Some code is shown in appendices I and J.

In terms of usage, doctors can simply log on to the web platform, as shown in appendix F. They can then see a table of their patients shown in appendix G, where patients below an adherence threshold, calculated by integrated machine learning algorithms, will be highlighted in red, as they require attention. Doctors can then click into individual patients to learn more about their granular adherence history and patterns, with the ability to contact them for intervention, as displayed in appendix H. Even prior to logging into the web platform, doctors will automatically be alerted should patients show alarming signs, and can then utilize the platform to obtain more information and determine next steps.

E. Final status of the project and test results:

Overall, three working versions of the device were completed with an online platform ready to accept and analyze patient data.

In the original working version of the device, the dispensing mechanism worked 99% of the time out of 100 trials at slight variations in angle as each test was done in hand to simulate a normal use case. In this case as well, the IR sensor always detected a pill being dispensed. This part of the device yielded mixed results in the smaller prototypes; however, this occurred primarily due to inconsistent lighting as they were made to be split open and with a fully open internal cavity as prototypes. This was overcome in the original model, and would be overcome in these as well, by using a consistent material to produce the device and in a fully encompassing piece. These dispenses in the original resulted in an average dispense time of 2 seconds and with these 99% occurring within 5 seconds. As mentioned above, battery life was estimated to be 5 days on the non-IOT version. Total MCU memory utilization of the program was only a maximum of 68% on the IOT version, meaning that there was still ample room remaining for data collection. On the IOT version too, Wi-Fi pairing and connection time was under 5 seconds on average which is well within a reasonable time to connect.

To achieve our analytics requirements, we utilized AWS Dynamo DB, a fast, flexible NoSQL database service, displayed in appendix K. By encrypting patient data both in transit (while being accessed) and at rest (while simply in storage), patient data protection was ensured. At the same time, speed was not sacrificed; reading data from Dynamo DB takes on average 12ms, ensuring fast access times. Batch writes to the database for an entire week's worth of data took only 21ms. Finally, as a dynamically resizing storage system, Dynamo DB is able to allocate just the minimum resources required at any given point in time, resulting in highly affordable rates in terms of cost: just $0.25/GB each month.

Finally, using AWS also allowed us to achieve our goals with the doctor-facing patient data platform. This platform needed to pull and analyze patient data using integrated machine learning algorithms to calculate patient adherence in real time. To do so, we used AWS S3 to host a static website towards this end. Doctors were authenticated using AWS cognito in the backend, ensuring that only they could access patient data in a secure manner. Algorithms were executed and computed in a scalable way, with low computational complexity providing them the ability to calculate adherence rate in real time as data in Dynamo DB was updated. Daily costs on S3 and Cognito came out to $0.06/day, coming out to an affordable $22/year.

F. Overall Evaluation:

The results of the PillBot device do seem to constitute a successful senior design. Working prototypes were created that could be put in the hands of patients to receive feedback. While each model of the device offers areas for improvement, every key technology that PillBot desired has been executed fully in one version of the device.The only failure in dispensing in the best version was alleviated by gently shaking the device to dislodge the stuck pill. However, we believe that these results are still more than satisfactory due to the nature of how these prototypes were constructed: 3D printing and assembled by hand. While these methods are quite good for rapid prototyping, if PillBot were to be implemented on a mass scale, the devices would surely be manufactured by some more reliable, faster, and cheaper method like injection molding that would eliminate the present irregularities and lead to a more consistent result.

Similarly, power consumption in the core version of the device at scale could likely be lessened. While the ATTiny85 does consume slightly higher power than alternative microcontrollers, lessening its power budget would not impact the final design much as the motor consumed more power in our testing. This could likely be best fixed by partnering with small motor manufacturers to order better suited components at scale, or possibly even working with a manufacturer to develop a motor better suited to PillBot's use case than what is currently accessible. If no better motor alternative can be implemented, a recharge circuit can be added to this core version of the device despite this being against the design philosophy as we wish to minimize its cost and not force patients to alter their workflow as much as possible. However, this is all only to improve the current capabilities of the device which already succeed in meeting the needs of the initial target market, a five day opioid prescription.

On the data side, these results do seem promising and provide a strong base from which the analysis will be built when acquiring actual patient data. Furthermore, the mitigation of computation time and complexity determined here will work to create faster responses for doctors on a larger scale and to minimize the operating costs of the PillBot web platform.

G. Conclusion:

In conclusion, three working prototypes of the PillBot device were created, each to address different needs of the healthcare space. The first design targeted patients who needed support for long term prescriptions. The second version of the device was a logical evolution of this first model as it was slimmed down to reduce complexity and cost while preserving the core functions necessary to best track adherence while not compromising patient workflows. This version of the device was also important as the team redesigned the internal dispensing mechanism and brought a fully custom PCB to fruition over the course of senior design. The third version of the device allowed for an alternative set of users to be brought into the PillBot ecosystem, clinical study participants and champions, as a result of the added IOT functionality. In parallel with these accomplishments, the PillBot data analytics platform was created to both provide doctors with a simple visual interface for viewing patient adherence and to digest this data, analyze it, and provide doctors with predictions of what patient trends may be in the future in order to facilitate them giving the best treatment possible. These algorithms were developed using preliminary data sets that represent what future collected adherence data will look like and provide a strong basis for which

V. **Business Plan and Model**

Stakeholders

PillBot's combination of a hardware device and software data platform is specifically designed to integrate across the five primary stakeholders directly involved in the PillBot workflow: patients, providers (insurance), doctors, pharmacies, and hospitals.

PillBot's primary users consist of first-time pain medication patients who receive their prescription pre-packaged in PillBot devices. These devices are sponsored by insurance companies, who receive the benefits of more adherent, and therefore less costly customers. Insurance companies also receive anonymized adherence data allowing them to make better rate approximations overall for large groups of patients. Hospitals, integral to the distribution flow of PillBot, lose $6.8B annually due to the readmission costs of nonadherence. With PillBot, hospitals face a decreased likelihood of readmission, resulting in significant cost savings. Doctors prescribe PillBot, and receive patient data so that they may tailor treatment regiments to patient needs. Finally, pharmacies are the primary distributors of the device, and give pre-loaded PillBot devices to patients and take in returns.

The value PillBot offers to stakeholders other than insurance is more difficult to quantify. For patients, opting in to PillBot makes adherence easy, through the device's robust dispensing mechanism, incentivizing patients to take medication exactly as prescribed. This is particularly relevant to chronic opioid patients receiving their prescriptions for the first time, usually due to pain arising from injuries or surgery. As a preliminary segment, we first aim to target patients prescribed opioids for acute back-pain, one of the most common reasons for opioids usage. This segment consists primarily of working adults, requiring a portable solution, for which PillBot is a perfect match.

Pharmacies are also directly incentivized to increase adherence. As part of the Affordable Care Act (ACA), the US government will provide grants to any pharmacies that implement some form of medication therapy management (MTM) services when treating chronic disease (Sec. 3503). To qualify for MTM reimbursements, pharmacies must individually apply for approval with insurance - and with PillBot having already gained the support of insurance companies by directly targeting medication adherence, pharmacies directly benefit from partnering with PillBot.

For hospitals, in addition to their losses due to readmission costs of nonadherence, there are several other indirect incentives for hospitals to partner with PillBot. For instance, over the past decade, a significant portion of hospital spending was directed towards implementing electronic health records (EHRs). With pressure from the American Reinvestment and Recovery Act to implement EHRs across hospitals, there is more motivation than ever to have full control and oversight over prescription data, for which PillBot brings existing data platforms to the next level.

Market Opportunity

Even beyond just doctors and patients, the nonadherence problem has immense repercussions on the entire US healthcare system. Each year, medical nonadherence costs the country's healthcare system $272 Billion dollars. Taking a look at that breakdown, for chronic opioids alone, insurance companies alone lose $4.5B on nonadherent chronic opioid patients and hospitals lose $6.8B on just the readmission costs of nonadherence.

Customer segments

PillBot has worked to engage with its potential customer base in several ways. First and foremost, PillBot conducted a series of MTurk surveys to poll individuals on a large scale on potential ideas and future directions. Such data gathered here includes pricing, demographics, and privacy expectations. PillBot has also spoken with several people who have suffered from addiction in order to better understand what we should do in order to best help people in a responsible and ethical manner. Some key insights stemmed from these talks including the importance of preventing addiction before it happens and a sense of confidentiality with user data. In the current development of the device, PillBot is working to gain incremental feedback from people representing all aspects of the potential user base in order to gauge reception of each decision. Some important instances of this feedback include device sizing and ergonomics, shape and color, and workflow versus that of a typical prescription regiment.

Size and Growth of Market

Every year, insurance spends an additional $3272 just on nonadherent chronic opioid patients (of which there are over 1.5 million in the US) compared to those that are adherent, resulting in a total of $4.9 billion wasted; with the number of nonadherent chronic opioid patients growing by nearly 11% each year, this cost is rapidly growing. By significantly improving patient adherence to addictive medications, PillBot has the potential to address this problem as an entry market.

Competition

While several solutions attempting to address nonadherence exist on the market,they are almost entirely B2C, requiring customers themselves to actively seek out a solution and bear its cost. Additionally, without looping in care providers, such solutions leave the value of adherence data almost completely unrealized. The four current segments of solutions can be defined as follows:

Non-IOT Pill Organizers: These take the form of weekly pill organizers, where the patient puts their correct daily doses at the start of the week, so they can take them without thinking later. They are extremely cheap and highly portable with a simple workflow, but lack a reminder system for patients and an adherence tracking system for caregivers.

Pill Dispenser: One of the most common categories is the pill dispenser, of which the most prominent example on the market is Hero. These are prohibitively expensive and saturated with competitors. They often include a reminder system, but also often charge extra for endless, recurring monthly fees, and lack portability.

Reminder Systems: There are very few competitors in this space, but some examples include Elliegrid and Adheretech. While these solutions are usually quite portable, and serve as good reminder systems for the patient, they are often extremely expensive, and do little to loop in care providers. Furthermore, there is no perfect solution for a given quantity and shape of a set of prescriptions. Patients must make do with the fixed number of dividers/spaces available, and there is little stopping them from simply taking more pills out of the standard containers.

Special Packaging: These are very cheap and offer a simple workflow for the patient, but require a high switching cost for patients, involving several frictions to registration including changing their pharmacy. Additionally, while individually packaged pills are super portable and often come with a reminder app, they present little to no data in terms of adherence.

Cost of Manufacturing

Manufacturing costs for the PillBot device at scale were designed to be kept to a minimum. Electronics are the largest recurring cost with the PCB at scale costing $3 and the motor and battery each costing $1. Plastic used to make up the dispensing mechanism and outer shell is quite inexpensive at $0.50 per unit after developing molds. These molds pose one of PillBot’s greatest upfront costs though as the unique shaping of the dispensing mechanism and number of individual pieces that are needed can cost up to $80,000. However, the electronic components can be recycled into new devices, meaning that as long as units are returned, these costs are not recurring. Batteries and plastic however must be paid for each time a device is built and handed to a patient.

Revenue model

Pricing PillBot at $1000 per year, per patient ensures that insurance companies that partner with PillBot save $3.4 billion per year on their current expenditures on nonadherence. This results in an achievable profit of $1.5 billion annually for PillBot - which is a very conservative estimate for only chronic opioids at a manufacturing cost of $10/new device.

Furthermore, the novel granular medical adherence data PillBot collects has the potential to revolutionize healthcare in the long run. Our analytics platform will alert care providers to alarming patient behavior, enabling them to take preventative measures. Additionally, doctors will better be able to understand addiction and patient behavior, facilitating tailored treatments that lead to improved patient outcomes. Due to the novel nature of the data market, its exact value is difficult to estimate; however, with hospitals losing nearly $7 billion annually on the readmission costs of nonadherence, this market is likely even larger than the former. In fact, selling anonymized data directly to insurance companies serves as PillBot's main long-term revenue stream, with the profits made from the devices themselves acting as secondary streams.

VI. **Self-learning**

A. Applicable Subject Areas

The greatest knowledge that the team gained over the course of senior design was industry understanding of the healthcare space and the requirements for bringing a hardware project to the market. Specifically through speaking with stakeholders and possible investors, the team learned about the challenges of launching a hardware project and the importance of key milestones such as testing, feedback, and profit margins. These lessons can clearly be seen in the evolution of prototypes developed during senior design, each with a key improvement tailored to meet stakeholders' needs.

In terms of the software and analytics side of PillBot, because the data we were working with was new, much of what we were doing was novel, requiring self-learning on our part. To do so, we studied existing literature on machine learning and probabilistic models, and tested them out through trial and error. Additionally, integrating all of this into a real-time frontend website was not a simple task. While the frontend of our data platform was straightforward, we had to expend far greater effort on determining how to integrate the backend, with our data and algorithms, in a meaningful and computationally efficient way. While we didn't have much experience with this, classes such as CIS 555, internet and web systems, were of particular use with this task, involving cloud computing aspects.

Additionally, the team gained valuable experience and knowledge in the areas of physical design and prototyping for mechanical systems. Specifically, determining manufacturing methods that would produce parts in a reliable manner and designing them to interact with each other in a consistent manner, even after wear, were novel concepts. On the electronics side, the team too gained experience working with vendors to check manufacturability for the PCB and assemble it.

B. Useful Classes

Chris - Human Systems Design: ESE 543, Ethics in an engineering project: EAS203, Circuit assembly ESE215 and ESE350, Project Management and Business: MGMT301, ACCT102, and ESE444, Prototyping and Manufacturing: OIDD415, ESE516, and ESE292

Bryan - PCB design and manufacturing: ESE292 and ESE516, CAD Design: MEAM 201, Microcontroller Programming: ESE 350, Power Electronics: MEAM 510, Manufacturing Techniques: IPD 515

Srisa - Machine Learning courses: CIS 522, CIS 581, CIS 520, ESE 514. Software Development: CIS 120, CIS 121, CIS 555. Data Analytics Courses: STAT 476, STAT 431, STAT 442, OIDD 930, OIDD 931. Finance/Budgeting: FNCE 207, FNCE 717, FNCE 205, ACCT 101, ACCT 102.

VII. **Ethical and Professional Responsibilities**

A. Professional Responsibility

Opioid use disorder affects over 2 million people in the United States each year, resulting in thousands of deaths and billions in excess medical expenses. PillBot stands in a unique position to solve not just this initial problem, but all medicine non-adherence related problems from the previously mentioned opioids to life saving and time critical cancer drugs.

To accomplish this, PillBot is priced quite inexpensively at a maximum of $10 per new device to encourage insurance companies to fund its usage and recuperate their lost profits. This recovery exists in two key ways.

First and foremost, patients receive their medication in a form that is actively designed to only administer the correct dosage at the correct time, although additional medication can be dispensed if the patient holds down the button for 30 seconds in a conscious and prolonged choice. This alone should lead to a reduction in overtaking. Undertaking is also addressed by the device notifying users when it is time to take their medication. Even if patients were to deviate from their prescription and were to face negative health outcomes as a result, with PillBot, doctors would be aware of this and would be able to alter future prescriptions accordingly. Furthermore, if using the IOT version of the device, loved ones or doctors could be contacted immediately to intervene and help the patient should a problem arise.

Secondly, the mass data collected by PillBot can be used to establish true adherence trends and allow insurance companies to properly gauge risk when choosing and reimbursing drug manufacturers, giving them another incentive to use PillBot. It should be made clear that PillBot will never share identifiable information with insurance companies and will only report anonymous bulk information to prove efficacy.

The room for PillBot in the healthcare space is created by the lack of a current solution that offers a solution to every problem. All existing offerings are either not portable, do not track adherence, or do not actually do anything to stop non-adherence at the moment it is occurring.

PillBot, with its small design, electronic dispensing and logging, and implementation of force dispense stands in a unique position to solve these problems in one solution. This is all on top of the business strategy of selling directly to insurance companies so that patients never have to bear the burden of loading or paying for the device.

B. *Ethical Issues*

The first ethical issue that was faced in PillBot's development this year was who to share data with and to what extent. After speaking with advisors, patients, and our classmates, the decision was ultimately made to share granular data only with doctors and loved ones, if the patient permitted. Sharing data with insurance companies is however the primary financial question with PillBot as these companies are the ultimate reimburses. As a result, some data must be shared with them to prove the efficacy of the device in increasing patient adherence. To accomplish this without intruding on patient privacy, only bulk data that cannot be tied to individuals will be shared with insurance companies.

Second, the design of the PillBot device must be done so that no groups of people are ostracized or harmed as a result. In aim of this goal, PillBot is designed to be accessible by a single hand and by a range of hand sizes. While this does work under the assumption that the patient has some range of motion in one hand, this is an acceptable understanding as the currently used standard pill bottle requires two fully functioning hands to open. Furthermore, to avoid alienating any economic groups, PillBot has been cost optimized as much as possible, and targeted at health care companies in a B2B manner so that patients never have to pay for better treatment.

The next key factor that we must consider is any form of stigma that may be placed upon those who use PillBot. In order to mitigate and prevent any social harm that could befall on users, PillBot has been made to be as discreet as possible and entirely opt in on the patient end. This patient choice ranges everywhere from what data is shared, to whom it is shared, and even whether or not to use the device in the first place. However, it is our belief that patients will opt into using PillBot as a majority of the individuals surveyed actually wished for some kind of a device to help them prevent addiction, as long as it was in a portable and uninterrupted way.

VIII. **Meetings**

In the fall, we spent much of our time meeting with stakeholders and members of the Penn Health Community, mostly over zoom, in order to gauge which directions we should be taking PillBot. This is where our major design decisions stemmed from, such as a slimmed down core device. Individuals we met with include VCs, Dr. Ari Brooks, Dr. James Weimer, and Dr. Insup Lee. We also continued these discussions after completing our prototype in order to gain valuable feedback from individuals who represent our key stakeholders, leading to our decision to miniaturize the handheld device.

Throughout both semesters we met with our advisor Dr. James Won who critically helped us interpret the information that we gathered from our meetings with stakeholders and actually make the design decisions that would give PillBot the best chances of success when being put in the hands of patients. These meetings happened on a weekly or bi-weekly basis, depending on what was occuring at the time.

We also met with our ESE advisors Sid Deliwala, Dr. Jan Van der Spiegel, and our TAs throughout the semester to determine our next steps, identify part sourcing, and envision what PillBot's ultimate goal should be. These meetings usually happened on a bi-weekly or monthly basis but also greatly varied by milestone.

IX. **Schedule with Milestones**

PillBot entered the spring semester with the following schedule.

Design PCB		12/20	
Finalize PCB and Have Manufactured		12/25	
Design Cloud Platform			1/15
Assemble Devices	1/20	1/20	
Integrate Devices with Cloud Platform	2/5		2/5
Generate IBX Report	3/10	3/10	3/10
Modify Device Based on Trial Results			3/10
Finalize Development of Machine Learning Model	4/1		
Redesign Marketing Site	4/1		
Launch Second Funding Round	4/1		4/1
Complete Feasibility Study with IBX	5/1	5/1	5/1

However, the team changed the schedule to reflect a longer lead time in receiving the resin printer and to give more time in iterating the design.

Task	Chris	Bryan	Srisa	Status
Re-design Cloud Platform Interface			1/30	Done
Implement an AI algorithm on AWS (Any accuracy)			2/10	Done
Develop SLA version that an physically be assembled with a <1in diameter	2/10			Done
Print 1st 3D Enclosure with Resin	3/16			Done

Manufacture PCB		3/20		Done
Assemble Devices with dispensing time <=2s		3/25		Done (Delayed)
Implement an AI algorithm with >70% accuracy			3/25	Done
Achieve an IOT Version that can communicate with AWS (Added part way through the semester)		4/1	4/1	Done
Launch Second Funding Round	4/1		4/1	Not Done
Complete Feasibility Study with IBX	5/1	5/1	5/1	Not Done

Ultimately, the major milestones of the project were met with the primary goal of achieving a working prototype that could put data on the online platform. Working prototypes and a functioning AI platform were developed with success by the dates set forth in the beginning of the semester with the only exception being the actual assembly of the devices. This deadline was delayed until before demo day and TED-S due to delays in ordering the PCBs caused by sickness and difficulties encountered with the dispensing mechanism and the printer. However, the team was still able to finish the prototypes before demo day which was deemed a success. The milestones that we were unable to hit included actually running a feasibility study with our devices and fundraising. These two points are related as we were unable to raise the funds necessary to acquire a clinician to actually run the study. It is the hope of the team that the development of the IOT version of the device will encourage clinical study teams to use PillBot as part of their studies since they can actually gain real time insight into their participants' behavior with the device; whereas with the non-IOT version, the trial would have almost solely been to test the efficacy of PillBot.

X. **Discussion of Teamwork**

PillBot's well-functioning team met on a bi-daily basis this semester both in-person and over zoom, and had weekly scrum meetings to ensure development was happening both asynchronously and as a team. Furthermore, addressing the opioid crisis is a very personal mission for this team. A few years ago, a close family friend was involved in a car accident and had his leg amputated. To deal with the pain, his doctor prescribed him opioids. Despite a strict prescription schedule and frequent clinical visits, he was crippled by addiction. The big question was why - despite his strict prescription, the only thing stopping him from taking more pills in a moment of irrationality was the simple lid on a standard pill bottle. It was evident to our entire team that the current system was broken. Hearing about the magnitude and devastation of the opioid crisis through the media only served to affirm this belief. As a result of this call to action, we as a team wanted to do all we could to ensure that no one else would have to struggle through a similarly painful experience; as a result, PillBot was born.

While opioid abuse has been a major issue in the US for the past two decades, over the course of the pandemic, the opioid crisis has escalated to new levels, with deaths relating to overdose increasing by a staggering 30% in 2020. In light of this, the value PillBot brings as a solution to the country's struggling and overloaded healthcare system is more critical than ever.

We believe we are the best team to tackle this issue, bringing both technical and business managerial knowledge to bring PillBot's vision to life.

Christopher Lee is a senior in the Management and Technology program at Penn studying entrepreneurial management and electrical systems engineering. As business/vision lead, he brings a significant amount of entrepreneurial and managerial experience to the table, having built several startups from ideation to acquisition over the past several years. It is his role to deliver pitches, gain funding, and coordinate the optimal business plan and product vision and communicate these details to the engineering team. As an experienced project manager with internship experience from both health-tech startups like Precise Software to large firms like Microsoft, he acts as the main bridge between pure business plan/financials and product development. Additionally, with significant experience in 3D modeling/electrical engineering as well as market research and customer discovery, he is at the perfect vantage point to deeply understand both customer needs and how they relate to the technical details of the product. On the engineering side of things, Chris handles the physical enclosure of the device, and works closely with Bryan to develop the PCB/electrical engineering components.

Srisa is a senior in the Management and Technology program at Penn studying computer science, finance, statistics, and submatriculating for a masters in mathematics. Having practical experience with data analytics and software development through internships at firms including Jane Street and Amazon, he has led the technical work on PillBot, including the website, app, as well as the adherence tracking platform. Furthermore, he has had experience consulting in the healthcare industry (for a Fortune 100 company), giving him knowledge of the industry as well as the regulatory landscape. Finally, as a finance major, Srisa has provided insight to hone down the company's business model, and manage finances.

Bryan is a second year master's student and senior in electrical engineering. Given his strong knowledge and experience in prototyping across different materials in classwork (aluminum, steel, plastic, etc), he has been the primary lead on the physical design and modeling of PillBot. With his knowledge of circuitry, Bryan has additionally focused on enabling the WiFi / Bluetooth connectivity of PillBot that allows it to communicate with Wi-Fi as well as to actually actuate the dispensing mechanism. Using his experience from designing industry standard electrical parts as a part of Penn's Electric Racecar team, Bryan works to integrate these electrical and mechanical systems onto a compact PCB with a focus on minimizing size, cost, and power consumption while maintaining a high level of robustness in the design.

XI. **Budget and Justification**

Resin Printing and Rapid Prototyping

Over the course of developing PillBot, we primarily used standard FDM Plastic printing via the Prusa i3 Mk3s printer, which we had previously owned before senior design. While some senior design funds were allocated to purchasing new rolls of filament for said plastic printer, we soon realized that an alternative solution was needed for even faster prototyping and higher quality printing. As such, we decided to make the significant investment in a resin printer from Prusa, which was able to cut our per-unit manufacturing time down from 8 hours to a single hour on fast mode. This allowed us to rapidly produce prototypes and garner quick user feedback, A/B testing in different resin and plastic colors. Overall, the budget allocation for the resin printer and resin printing was $3,000 for the printer itself, plus $600 for materials. This included the automatic resin curing station, several gallons of isopropyl alcohol for curing, and the resin itself, in addition to the FEP films, which had to be replaced every 20 prints or so.

PCB and Electronics Manufacturing

PCB costs were relatively high due to the low unit count and urgency in ordering. Three copies of the PCB were ordered from Advanced Circuits costing $248.01 after shipping as part of their $33 per board service which limited board complexity and internal cavities. Components on the board used in assembly were all sourced from labs within engineering and contributed no extra cost to the project, however if components were to be ordered, they would have cost less than $5 per board. Motors were relatively expensive as well as about $10 per unit, but this high cost is again primarily due to the low order quantity and uniqueness of the part. If the PCBs and motors were ordered in bulk, each would likely have cost between $2-5 per part. These supplies were funded through pitch competitions.

XII. **Standards and compliance:**

The standards that the PillBot device must comply with are broken down into three main categories: health, assembly, and usage.

For health standards, the device must comply with FDA regulations and HIPAA guidelines. For FDA certification, PillBot is designed to fall under Class 1 certification with 510k exemption meaning that there would be as low of a barrier to entry as possible. Design decisions made here are done to ensure that our device is deemed as a low risk for patients and to utilize existing precedents as a physical medication dispenser and medication reminder. These design decisions include a two step access to medication, never stopping patients from accessing their medication through an ability to “force dispense” or removal of the side panel, and by giving patients new PillBots at every prescription. HIPAA compliance is more of a concern on the data end, but the handheld device takes this into account as well, specifically from the IOT end, as it only communicates with the secure PillBot web platform and not directly to any other third parties.

Second are manufacturing and assembly standards such as RoHS, IPC, and ANSI. To comply with RoHS and thus reduce the contribution to hazardous substances in the environment and being exposed to people, PillBot is assembled without such materials, namely lead. IPC compliance ensures that designs made, specifically for the PCB, are actually capable of being manufactured by vendors and are confirmed when actually designing components in Altium and again when sending processing files to PCB manufacturers to verify that the design meets their specifications. Lastly, an upholding of ANSI standards in CAD drawings ensures that any physical dimensions are conveyed clearly and accurately to manufacturers.

Last but not least are standards that govern the actual operation of the device. These standards primarily are composed of IEEE 802.11, 10472, and 1752.1. For 802, PillBot in its current iteration satisfies this requirement by using existing microcontrollers to communicate wirelessly that already follow these and FCC guidelines when being sold in the US. When PillBot moves to using a custom PCB though for IOT, these considerations on signal must be included. To uphold 10472, PillBot is designed to be as platform neutral as possible with current online access being done over simple yet secure web pages that can be accessed via any device. Additionally, charging in the IOT version can be done over a widely used and available micro-USB cable. Lastly, any mobile implementations will be made available to both IOS and Android users so as to not alienate patients. Lastly to comply with 1752.1, PillBot works to ensure that any data being exhibited to patients or their doctors is done so in as clear of a way as possible so that this information is not misinterpreted, yet still able to be quickly digested.

XIII. **Work done since last semester**

Since the end of senior design in the fall, the team has hit several key milestones in the design implementation of Pillbot. First, a fully functioning prototype was finished that fit inside the form factor that was arrived at in December of last year. This was done with a fully custom PCB that was designed over the course of spring, ordered, and soldered by hand. Additionally, the team also implemented an IOT version of the device using and off the shelf ESP-32 that would allow for constant internet access. The final major development was a fully working and tested version of our analytics platform that would process adherence data in real time.

XIV. **Discussion and Conclusion**

Our time spent on PillBot over the course of senior project has truly allowed us to contribute towards our vision of revolutionizing the way prescriptions work. We’ve worked with experts and stakeholders across all spectrums, including our advisor Dr. James Won, a human systems design expert at CHOP, Dr. Ari Brown, a cancer specialist at Penn Hospital, IBX, a local health insurance company, pharmacists, and hundreds of opioid patients to understand the needs of these countless players, and gear our device towards satisfying them.

We’ve made our PillBot device smaller and more reliable than ever before, ready to be tested in the hands of patients in upcoming feasibility studies. We’ve additionally managed to train and test several machine learning algorithms to maximize the use of the novel granular adherence data PillBot collects, allowing doctors to improve care for their patients. Finally, we’ve worked tirelessly to develop our software data platform, recently achieving seamless IoT integration with our physical device.

We’ve learned countless lessons along the way, the greatest of them all being the importance of talking to stakeholders, from care providers at the forefront of their field to patients suffering with the problems we aim to address, we were given many recommendations and along the way that allowed us to pivot our device during its development. This greatly increased the speed at which we were able to iterate, allowing us to create a tailored, usable product much faster than otherwise. We’ve additionally learned more about the space than ever before, and have improved our technical skills through the span of this project, both with respect to hardware design and circuitry as well as software development and data analytics. We are currently happy with the engineering state that PillBot is in today with its core functionality defined and tested. Next steps here likely involve taking the IOT version and creating a fully custom PCB for it.

While we are proud of the progress we made on PillBot over the course of senior design, we recognize that the future holds many challenges. The timeline for FDA approval was one of the main issues we had in mind throughout the development process, and we've managed to design our device in such a way that it is 510k exempt, ensuring the simplest approval process possible (usually within 90 days). Additionally, in terms of our business model, there is much work to be done in terms of bringing our device to life. We first must prove the efficacy of PillBot in a feasibility study, after which, comes a large-scale trial. Towards this end, we've honed down our solution to be ready for patient use, and have spoken with IBX, who has agreed to sponsor a large scale trial given positive results from the feasibility study. We are currently in talks with investors to fundraise to ramp up our product manufacturing capabilities. Though these will be daunting tasks, we're excited for the road ahead!

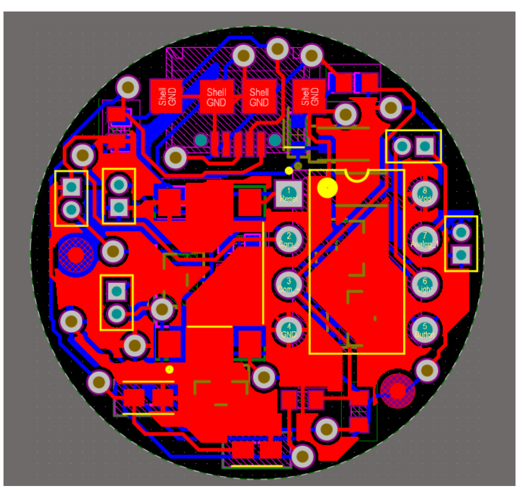
Finally, we would like to give a large thank you to all the support we have received from our many advisors: James Won, Siddharth Deliwala, Jan van Der Spiegel, Andrea Yoss, Aditya Hota, Brian Handen, and Sangeeta Vohra. Your support throughout every step of this process has been invaluable and has allowed us to reach new heights, even receiving the Judges Choice Award from the SEAS interdepartmental competition. Thank you for helping us bring the PillBot vision to life!

XV. **Appendices**

Appendix A:

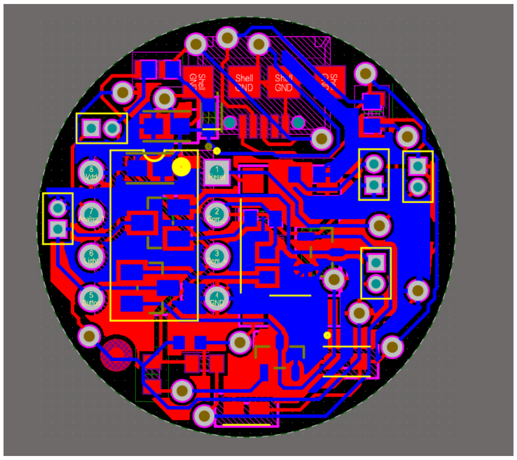
3D render of the final, trimmed down version of the device.

Appendix B:



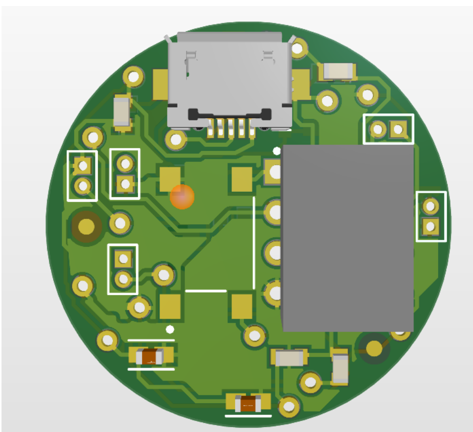
Altium view of the PCB used in the non-IOT version.

Appendix C:



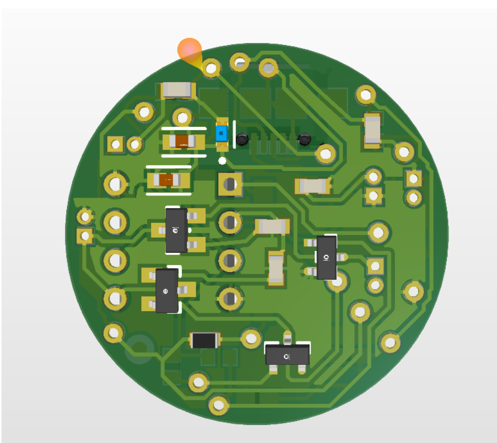
Alternative Altium view of the PCB used in the non-IOT version.

Appendix D:



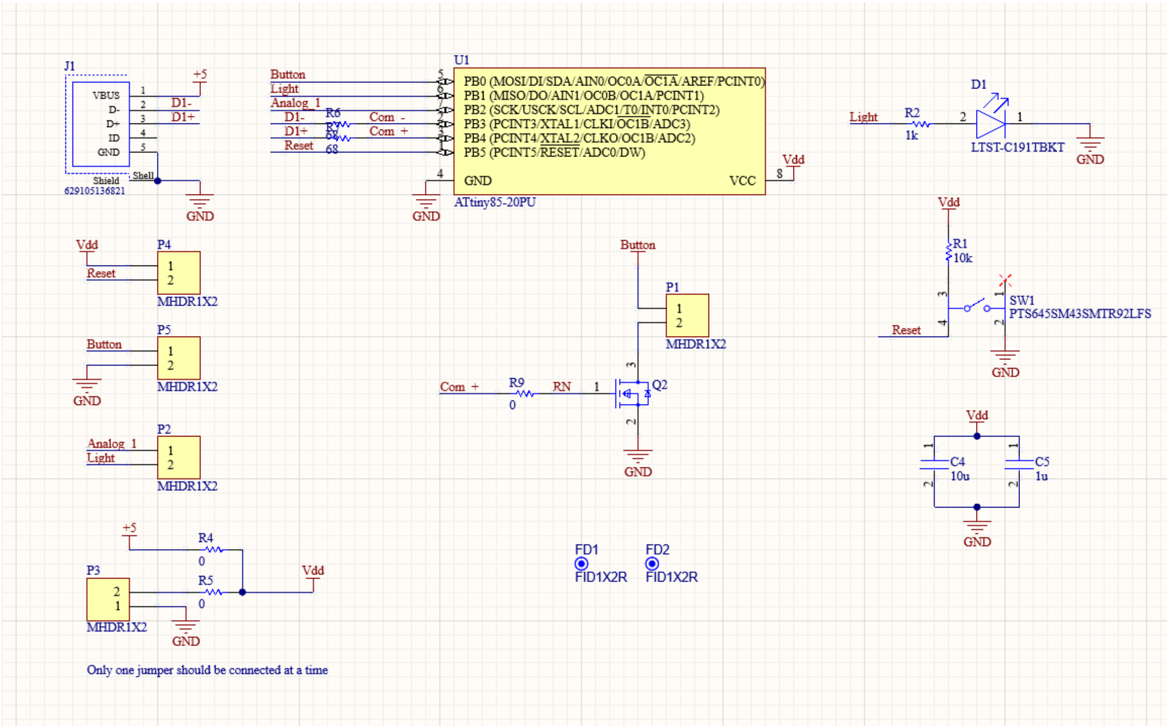
3D Altium view of the PCB used in the non-IOT version.

Appendix E:



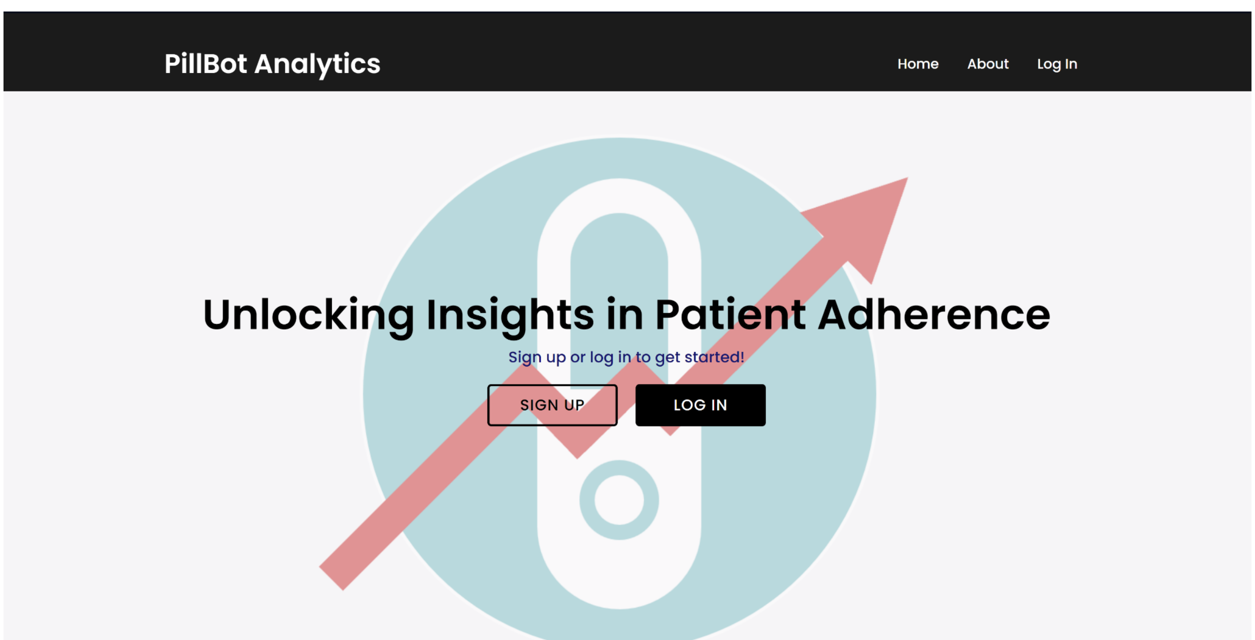
Alternative 3D Altium view of the PCB used in the non-IOT version.

Appendix E:



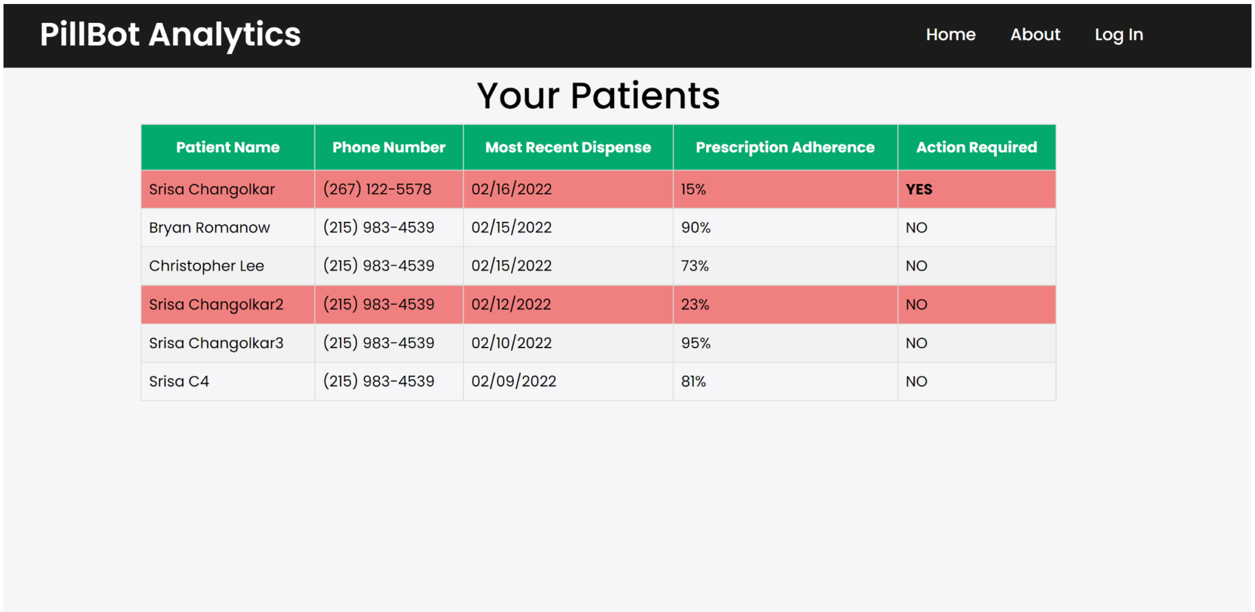
Altium schematic for the non-IOT PCB

Appendix F:



Home page for the data analytics platform.

Appendix G:



PillBot Analytics

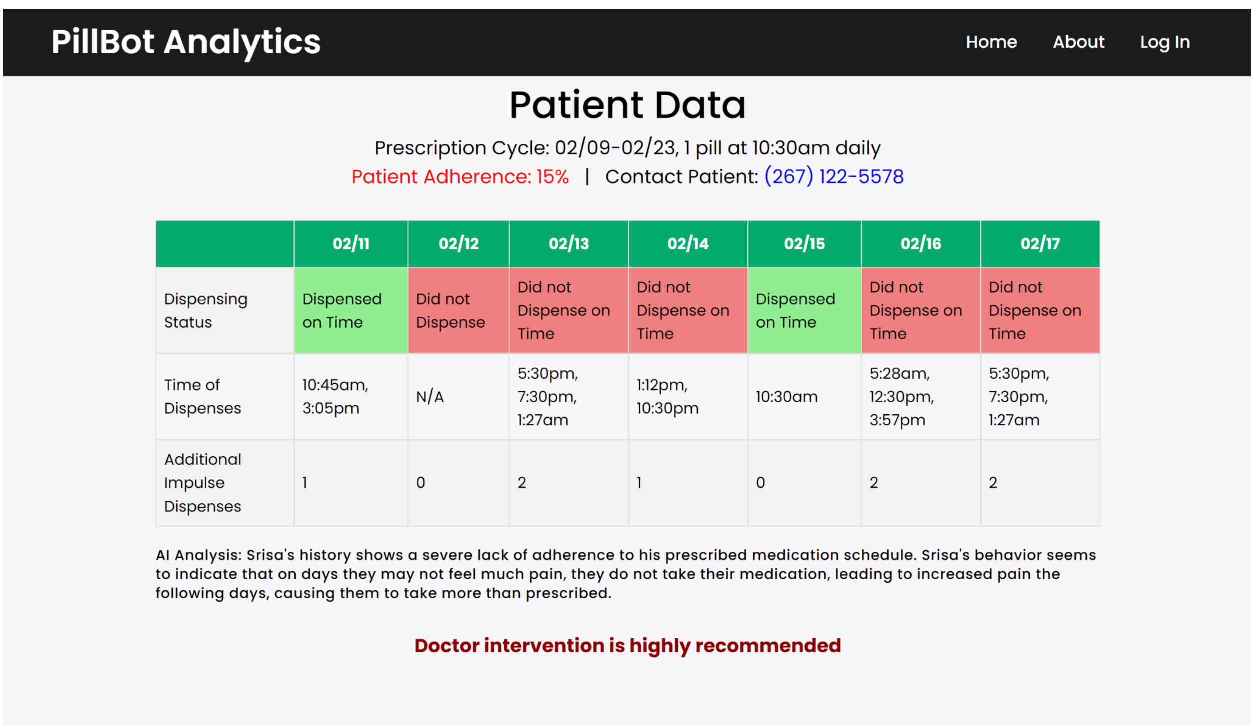
Home About Log In

Your Patients

Patient Name	Phone Number	Most Recent Dispense	Prescription Adherence	Action Required
Srisa Changolkar	(267) 122-5578	02/16/2022	15%	**YES**
Bryan Romanow	(215) 983-4539	02/15/2022	90%	NO
Christopher Lee	(215) 983-4539	02/15/2022	73%	NO
Srisa Changolkar2	(215) 983-4539	02/12/2022	23%	NO
Srisa Changolkar3	(215) 983-4539	02/10/2022	95%	NO
Srisa C4	(215) 983-4539	02/09/2022	81%	NO

Patient overview on the web platform.

Appendix H:



PillBot Analytics

Home About Log In

Patient Data

Prescription Cycle: 02/09-02/23, 1 pill at 10:30am daily

Patient Adherence: 15% | Contact Patient: (267) 122-5578

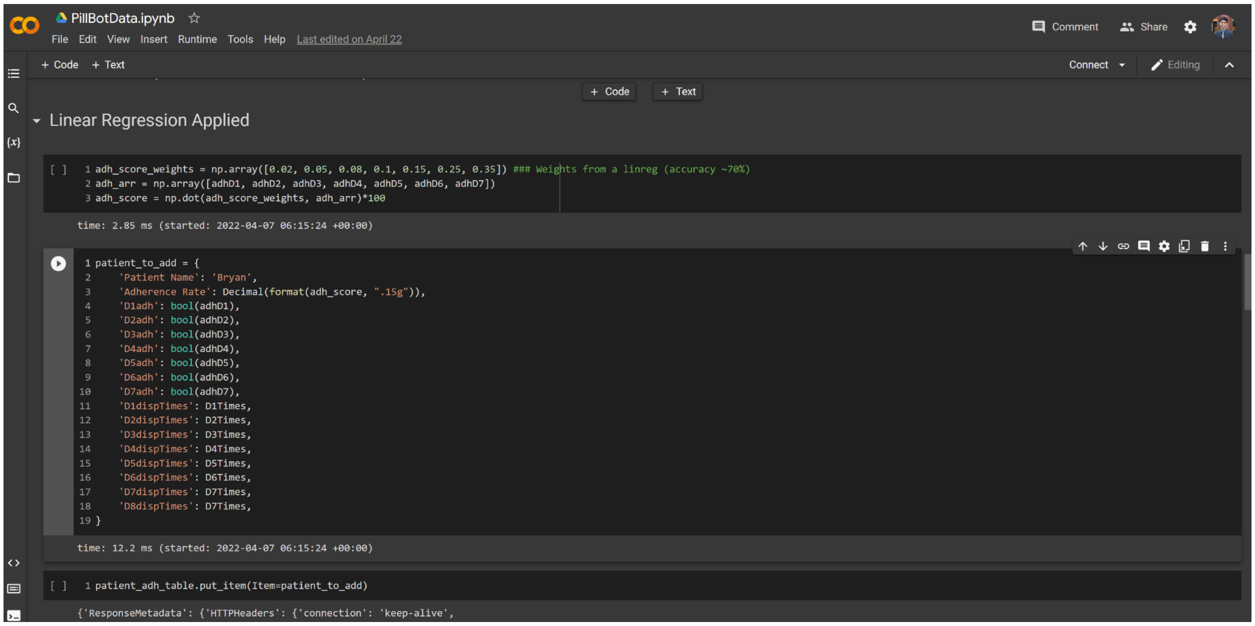
	02/11	02/12	02/13	02/14	02/15	02/16	02/17
Dispensing Status	Dispensed on Time	Did not Dispense	Did not Dispense on Time	Did not Dispense on Time	Dispensed on Time	Did not Dispense on Time	Did not Dispense on Time
Time of Dispenses	10:45am, 3:05pm	N/A	5:30pm, 7:30pm, 1:27am	1:12pm, 10:30pm	10:30am	5:28am, 12:30pm, 3:57pm	5:30pm, 7:30pm, 1:27am
Additional Impulse Dispenses	1	0	2	1	0	2	2

AI Analysis: Srisa's history shows a severe lack of adherence to his prescribed medication schedule. Srisa's behavior seems to indicate that on days they may not feel much pain, they do not take their medication, leading to increased pain the following days, causing them to take more than prescribed.

Doctor intervention is highly recommended

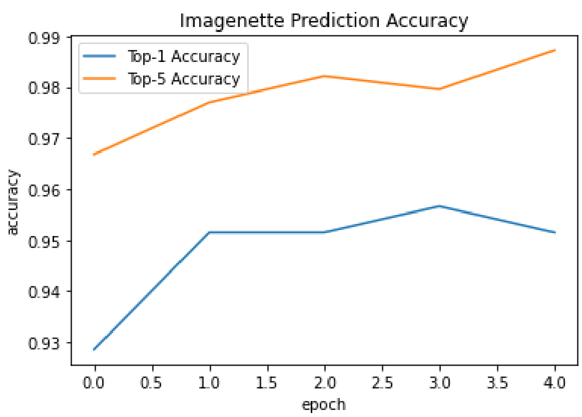
Patient specific view on the web platform.

Appendix I:



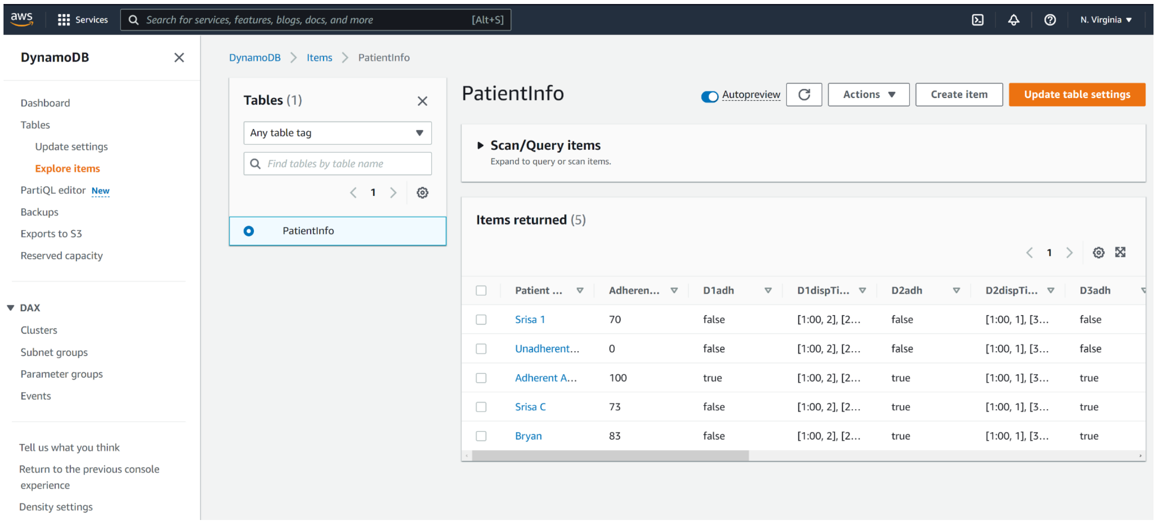
Linear regression weighting value results from data analytics platform.

Appendix J:



Prediction accuracy results from AI model.

Appendix K:

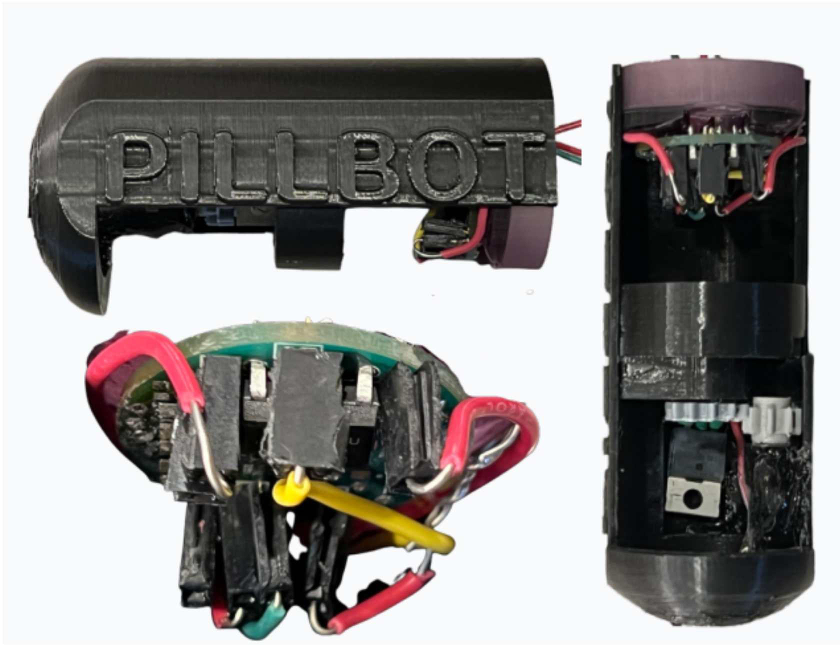


View of AWS IOT platform where data is uploaded too.

Appendix L:

First working prototype.

Appendix M:



Cross sectional view of functioning core device with custom PCB.

Appendix N:


Internal PillBot dispensing mechanism

Appendix O:

```
//WIP IOT Code

#include <WiFi.h>
#include <WebServer.h>
#include <NTPClient.h>
#include <WiFiUdp.h>
#include ""sch.h""
#include ""secrets.h""
#include <WiFiClientSecure.h>
#include <MQTTClient.h>
#include <ArduinoJson.h>

// The MQTT topics that this device should publish/subscribe
#define AWS_IOT_PUBLISH_TOPIC   ""PillBot/pub""
#define AWS_IOT_SUBSCRIBE_TOPIC ""PillBot/sub""

WiFiClientSecure net = WiFiClientSecure();
MQTTClient client = MQTTClient(256);
String user = "Bryan";
void connectAWS()
{
  WiFi.mode(WIFI_STA);
  WiFi.begin(WIFI_SSID, WIFI_PASSWORD);

  Serial.println(""Connecting to Wi - Fi"");

  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(""."");
  }

  // Configure WiFiClientSecure to use the AWS IoT device credentials
  net.setCACert(AWS_CERT_CA);
  net.setCertificate(AWS_CERT_CRT);
  net.setPrivateKey(AWS_CERT_PRIVATE);

  // Connect to the MQTT broker on the AWS endpoint we defined earlier
  client.begin(AWS_IOT_ENDPOINT, 8883, net);

  // Create a message handler
  client.onMessage(messageHandler);

  Serial.print(""Connecting to AWS IOT"");

  while (!client.connect(THINGNAME)) {
    Serial.print(""."");
    delay(100);
  }

  if (!client.connected()) {
    Serial.println(""AWS IoT Timeout!"");
    return;
  }

  // Subscribe to a topic
  client.subscribe(AWS_IOT_SUBSCRIBE_TOPIC);

  Serial.println(""AWS IoT Connected!"");
}
int num = 0;
void publishMessage(String text)
{
  StaticJsonDocument<300> doc;
  doc[""chip_time""] = millis();
  doc[""name""] = user;
  doc[""num_pills""] = num;
  doc[""Time""] = text;
```

```
  doc[""Time""] = text;
  doc[""force_dispense""] = force;
  char jsonBuffer[1024];
  serializeJson(doc, jsonBuffer); // print to client

  client.publish(AWS_IOT_PUBLISH_TOPIC, jsonBuffer);
}

void messageHandler(String &topic, String &payload) {
  Serial.println(""incoming: "" + topic + "" - "" + payload);

  //  StaticJsonDocument<200> doc;
  //  deserializeJson(doc, payload);
  //  const char* message = doc[""message""];
}

/*Put your SSID & Password*/
const char* ssid = """";  // Enter SSID here
const char* password = """";  //Enter Password here

WebServer server(80);

// Define NTP Client to get time
WiFiUDP ntpUDP;
NTPClient timeClient(ntpUDP, ""pool.ntp.org"");

//Week Days
String weekDays[7] = {""Sunday"", ""Monday"", ""Tuesday"", ""Wednesday"", ""Thursday"", ""Friday"", ""Saturday""};

//Month names
String months[12] = {""January"", ""February"", ""March"", ""April"", ""May"", ""June"", ""July"", ""August"", ""September"", ""October"", ""November"", ""December""};


uint8_t LED1pin = 15;
bool LED1status = LOW;

uint8_t LED2pin = 14;
bool LED2status = LOW;

void setup() {
  Serial.begin(115200);
  delay(100);
  pinMode(LED1pin, OUTPUT);
  pinMode(LED2pin, INPUT);

  Serial.println(""Connecting to "");
  Serial.println(ssid);

  connectAWS();

  //  //check wi-fi is connected to wi-fi network
  //  while (WiFi.status() != WL_CONNECTED) {
  //    delay(1000);
  //    Serial.print(""."");
  //  }
  //
  //  Serial.println("""");
  //  Serial.println(""WiFi connected..!"");
  //  Serial.print(""Got IP: "");  Serial.println(WiFi.localIP());
  //
  //  server.on(""/"", handle_OnConnect);
  //  server.on(""/led1on"", handle_led1on);
  //  server.on(""/led1off"", handle_led1off);
  //  server.onNotFound(handle_NotFound);
```

```
  //  server.onNotFound(handle_NotFound);
  //
  //  server.begin();
  //  Serial.println(""HTTP server started"");
}

int turn = 0;
int ogtime = 0;
int curtime = 0;
int force = 0;

void loop() {

  //  server.handleClient();
  //  if(LED1status)
  //  {digitalWrite(LED1pin, HIGH);}
  //  else
  //  {digitalWrite(LED1pin, LOW);}
  //
  //
  timeClient.update();

  time_t epochTime = timeClient.getEpochTime();
  //

/*
  Rui Santos
  Complete project details at https://RandomNerdTutorials.com/esp8266-nodemcu-date-time-ntp-client-server-arduino/

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*/

  String formattedTime = timeClient.getFormattedTime();
  //  Serial.print(""Formatted Time: "");
  //  Serial.println(formattedTime);
  //
  int currentHour = timeClient.getHours();
  //  Serial.print(""Hour: "");
  //  Serial.println(currentHour);
  //
  int currentMinute = timeClient.getMinutes();
  //  Serial.print(""Minutes: "");
  //  Serial.println(currentMinute);
  //
  int currentSecond = timeClient.getSeconds();
  //  Serial.print(""Seconds: "");
  //  Serial.println(currentSecond);
  //
  String weekDay = weekDays[timeClient.getDay()];
  //  Serial.print(""Week Day: "");
  //  Serial.println(weekDay);
  //
  //Get a time structure
  struct tm *ptm = gmtime ((time_t *)&epochTime);
  //
  int monthDay = ptm->tm_mday;
  //  Serial.print(""Month day: "");
  //  Serial.println(monthDay);
  //
  int currentMonth = ptm->tm_mon + 1;
  //  Serial.print(""Month: "");
```

```
//  Serial.print(""Month: "");
//  Serial.println(currentMonth);
//
String currentMonthName = months[currentMonth - 1];
//  Serial.print(""Month name: "");
//  Serial.println(currentMonthName);
//
int currentYear = ptm->tm_year + 1900;
//  Serial.print(""Year: "");
//  Serial.println(currentYear);
//
//Print complete date:
String currentDate = String(currentYear) + "" - "" + String(currentMonth) + "" - "" + String(monthDay) + "" - "" + String(formattedTime);
//  Serial.print(""Current date: "");
//  Serial.println(currentDate);
//
////  Serial.println("""");
//
//
//


int i = 0;
while (i < -1) {
  publishMessage(""dont"");
  client.loop();
  i++;
  delay(2000);
}
int x = digitalRead(14);

curtime = millis();
if (!x && turn == 0) {
  force = 0;
  if (currentHour == schedule[0] && currentMinute == schedule[1]) {
    turn = 1;
  }
  while (!x && turn == 0) {
    if (millis() - curtime > 5000) {
      turn = 1;
      force = 1;
    }
    x = digitalRead(14);
  }
  if (turn == 1) {
    ogtime = millis();
    digitalWrite(15, 1);
    num = num + 1;
    Serial.println(""..."");
  }
}
else {
  int a = 1;
}
if (turn) {
  if (curtime - ogtime < 2500) {
    int a = 1;
  }
  else {
    turn = 0;
    publishMessage(currentDate);
    num = num - 1;
    digitalWrite(15, 0);
  }
```

```
    }
  }

}

void handle_OnConnect() {
  LED1status = LOW;
  LED2status = LOW;
  Serial.println(""GPIO4 Status: OFF | GPIO5 Status: OFF"");
  server.send(200, ""text / html"", SendHTML(LED1status, LED2status));
}

void handle_led1on() {
  LED1status = HIGH;
  Serial.println(""GPIO4 Status: ON"");
  server.send(200, ""text / html"", SendHTML(true, LED2status));
}

void handle_led1off() {
  LED1status = LOW;
  Serial.println(""GPIO4 Status: OFF"");
  server.send(200, ""text / html"", SendHTML(false, LED2status));
}



void handle_NotFound() {
  server.send(404, ""text / plain"", ""Not found"");
}

String SendHTML(uint8_t led1stat, uint8_t led2stat) {
  String ptr = "" < !DOCTYPE html > <html>\n"";
  ptr += ""<head><meta name = \""viewport\"" content = \""width = device - width, initial - scale = 1.0, user - scalable = no\"">\n"";
  ptr += ""<title>Pillbot Dashboard < / title > \n"";
  ptr += ""<style>html { font - family: Helvetica; display: inline - block; margin: 0px auto; text - align: center;}\n"";
  ptr += ""body{margin - top: 50px;} h1 {color: #444444;margin: 50px auto 30px;} h3 {color: #444444;margin-bottom: 50px;}\n"";
  ptr += "".button {display: block; width: 80px; background - color: #3498db;border: none;color: white;padding: 13px 30px;text-decoration: none;font-size: 25px;margin: 0px auto 35px;cursor: pointer;border-radius: 4px;}\n"";
  ptr += "".button - on {background - color: #3498db;}\n"";
ptr += "".button - on: active {background - color: #2980b9;}\n"";
  ptr += "".button - off {background - color: #34495e;}\n"";
ptr += "".button - off: active {background - color: #2c3e50;}\n"";
  ptr += ""p {font - size: 14px; color: #888;margin-bottom: 10px;}\n"";
  ptr += "" < / style > \n"";
  ptr += "" < / head > \n"";
  ptr += ""<body>\n"";
  ptr += ""<h1>Pillbot"" + String(aaa) + "" < / h1 > \n"";
  //  ptr +=""<h3>Using Station(STA) Mode</h3>\n"";

  if (led1stat)
  {
ptr += ""<p>LED1 Status: ON < / p > <a class = \""button button - off\"" href = \"" / led1off\"">OFF < / a > \n"";
  }
  else
  {ptr += ""<p>LED1 Status: OFF < / p > <a class = \""button button - on\"" href = \"" / led1on\"">ON < / a > \n"";}



  ptr += "" < / body > \n"";
  ptr += "" < / html > \n"";
  return ptr;

```