Distributed Climate Control (DCC) - Project Summary

By Team **Slam Town**
Dan Coen
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Overview: Welcome to the Distributed Climate Control (DCC) project. This system will help businesses, homeowners, and other institutions save money on energy spending by dramatically reducing the amount of heating and cooling spent on air space that no one is occupying, as well as contributing to global efforts to create affordable, sustainable energy technologies. This project specifically aims to provide information specifying how many people are in a room, and where they are situated. This information will be used by a HVAC system which can target specific regions of a room. This project is inspired by the ARPA-E's research and funding of advanced energy systems.

Intellectual Merit: This Small Business Innovation Research Phase I project will have to effectively use a variety of sensors to obtain features to train an accurate machine learning model. The device will combine thermal, color, and depth imaging to track where in a room people are, and specifically how many people occupy certain areas so that an HVAC device could heat or cool only regions of the room occupied by people. The sensors used will be a flir lepton thermal camera and a kinect v2 RGB-D camera. Significant challenges of this problem include accurately calibrating the system in the room despite not having a long-range depth sensor, and making the system portable so that it can be placed at a high vantage point and out of the way from any of the activity in the room. Additionally, the device should be able to communicate to a separate, more powerful machine which can help with additional processing including training the headcount and distribution model. Due to the small field-of-view of the thermal camera and the need to combine the images of multiple sensors, the kinect and flir lepton thermal camera will have to pan and tilt to capture a full image of the room, requiring strong and accurate motor control to capture a point in time accurately in a short time frame.

Broader/Commercial Impact: This project will demonstrate a new method of saving energy in a way that is attractive to businesses and homeowners. The non-intrusive nature of our device combined with the amount of money to be saved by consumers makes a strong argument for the DCC's success on the market, and furthers research of sustainable and forward-thinking energy technologies. Additionally, the DCC will explore the ability to create a device with currently obtainable and affordable technology, strengthening the importance of an effective prototype.

Distributed Climate Control (DCC) - Elevator Pitch

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Heating, ventilation, and air conditioning make up 48% of the energy used in a typical U.S. home. HVAC makes up the largest energy expenditure of households, as well as many typical businesses. However, a great portion of HVAC resources are spent in locations where people don't even occupy, repeatedly heating and cooling air surrounding nothing. This is waste of money, and energy which could easily be solved by our product: The Distributed Climate Control system.

DCC is an embedded solution to today's HVAC problems. By using an assortment of sensors and S.O.C.'s, we have designed an inexpensive, accurate way to determine the number of people occupying a room, where they are situated, and how comfortable the air temperature surrounding them is. Using this data, HVAC systems will be able to target locations of a room where people exist and are situated in uncomfortable climates. This data will be collected real time, so that people entering and leaving the room will instantly allow the systems to know when to start and stop.

Our implementation involves using a Kinect RGB-D sensor to capture rigidbodies in the room as well as high resolution images. This data will be combined with a heatmap captured by the flir lepton 3 thermal camera in order to train a machine learning model which can be calibrated to work with variable sized rooms and large groups of people. The thermal camera will also be able to determine the relative temperature in room locations, meaning that the HVAC system can further save energy and money by shutting off if a well-populated region is already sufficiently cooled. Both camera modules will be mounted on top of a single automated pan and tilt bracket driven by servo motors, allowing the two sensor modules to synchronize their data easily and accurately.

There are several main problems that need to be solved in order for our system to have full functionality. One of these is training a machine learning algorithm to interpret our data and produce accurate information on population and heat distribution in a room. It is likely most of the training done for our machine learning model will be done by hand via counting the amount of people in the room and telling our algorithm the correct answer, or by having to build our own some type of program to assist us in training the model; in either case this requires a significant amount of time. Other problems that arise with this are data storage and getting real-time results. In order to train our algorithm and process all of the different types of data we are getting, we will need to be able to store large amounts of data. We will need to figure out the best way of storing/streaming our data to simplify this process. Obtaining results in real-time is also a large problem that we may run into. Since we are doing our processing on the UP Board, it could prove difficult to get our information routinely and reduce latency.

Distributed Climate Control (DCC) - Elevator Pitch (Revised)

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Commercial and Social Impact

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Introduction

The Distributed Climate Control project presents value in multiple areas. The project's success is assured by the nature of energy being a universally expensive as well as limited environmental resource. Not only will DCC be a successful business venture, but it will be an important research initiative into the still under-explored realm of machine learning and energy conservation.

The Commercial Opportunity

At first the product will be marketed towards large companies and businesses. Usage will be marketed as for conference halls and other large open areas. This is important as it will be much more difficult to market towards smaller spaces like apartments, homes, and small businesses. Later on, once it is proven successful in that field, it can be adjusted to be marketed for home use. It may be expensive and not beneficial in the short run for some small-space users. However with shown strength in use in industrial use, it would be more convincing. This combined with effective marketing and statistics should allow for marketability for homeowners.

The prototype model for our senior design project will cost around $800. This includes the 2 sensors, SOCs, wires, servos, and pan/tilt bracket. With streamlined production and better organization, the price could get as low as $400 for the setup. This does not include the actual HVAC systems that are being created for the distributed cooling and heating. That will be a separate setup and cost, which is up to the discretion of that team. Based on their project, it should cost around $1500. As described before, the customers in the end will be homeowners and businesses/companies. Again, at first marketing will be directed at large/small companies, as it will be easier to see the beneficial impact for those groups. These groups will have access to large conference-like spaces in all likelihood, where the system is designed to work optimally.Once proving that it works in this environment, it will be much easier to market towards homeowners. The DCC system works well in a large, open environment. Fortunately, these areas exist in many American homes. A living room in a suburban home, or a studio apartment; these are great places to put a DCC system, as the sensors are able to get a great view of the whole environment.

The competition for DCC is, in all likelihood, not going to change greatly by the time it enters the market. HVAC in its current form has existed for many years, and only in the past ~20 years has it evolved with "smart" technology and connection with the Internet of Things. These advancements work towards integrating many other services together for a simpler user-end experience. An example of one of these products is the Nest thermostat system. This product uses methods to find patterns in what temperature the user needs/wants depending on the time of day. Options or the temperature can be controlled from the user's phone as well. DCC actually does not necessarily interfere with this technology. It will still accept a certain temperature for a room, which could be set from the Nest, and just monitors/distributes air in a different and more efficient way than traditional HVAC. Other evolutions in the field involve air-purifying technology, reducing the amount of harmful particles present, increasing efficiency and reducing greenhouse gas emissions. DCC approaches air-purifying at a different angle, reducing the amount of greenhouse gas output by only heating or cooling one portion of a room at once. Thus the system is reducing greenhouse gas output in a different way than current air-purifying technologies. It also is somewhat independent, such that the air-purifying could be implemented for DCC without any major changes at all. Thus DCC does not have much competition in terms of other products providing the same service, the real risk is whether the changes it brings to the table are useful enough to be implemented.

Marketability is going to be significantly more difficult for smaller businesses and homeowners compared to larger groups. Again, as said before, marketing for larger businesses first is essential to establish a proof-of-concept to become more broadly marketable. The reasoning behind this is that for smaller residences and offices, the results in terms of lowered energy usage and costs would be less substantial and potentially not worth the cost of installation. Over time, DCC should be worthwhile for any moderately sized room, but for certain types it may be much longer before the benefits outweigh the costs. For example, in a living room of a person's home, if it is used frequently by multiple people at once, most or all of the HVAC systems may need to be used at once, making it behave similarly to traditional HVAC. Also, if a user in a suburban, two-story home wanted to install DCC all across their space, they would need multiple systems to account for each room. This could get expensive, and simply may not be worth it for the average homeowner. Bringing this back to the beginning, this is another reason why a more corporate/industrial marketing strategy at first is important. If DCC cannot succeed in that environment, it is extremely unlikely that it will be at all successful in other areas.

According to ARPA-E's DELTA program (https://arpa-e.energy.gov/?q=arpa-e-programs/delta), a system like DCC that distributes heating and cooling more efficiently throughout a room could reduce costs for a home's HVAC by 15%. Translated into actual cost reduction, this would result in around a $150 cost reduction per year. This is a substantial decrease, albeit with significant installation costs, and if marketed well enough, would be an important statistic to convince consumers to invest in DCC. These benefits would be even greater than 15% for places like large conference halls as discussed earlier, and should be even more convincing for companies.

Societal Benefits

This project is addressing the massive amounts of energy wasted in everyday life by cooling and heating air in which there are no human beings occupying. The current model of Heating and Air Conditioning homes and buildings is simply broken and outdated. Currently, 65% of energy in the United States is still supplied by burning fossil fuels, which is the largest portion of any other energy source currently in use. This is particularly bad because burning fossil fuels releases a lot of carbon emissions, and is very destructive to animal habitats.

An immediate benefit of the DCC project is reducing the usage of these environmentally damaging energy sources. By reducing the amount of total energy used both on a national and international scale, we can collectively move more towards clean energy options supplying a larger percentage of energy to handle the smaller load. During and after a development like this, the system is still effective; regardless of where the energy is being sourced, the DCC will use less of it. This is important for the continued of the DCC and energy use in general. The DCC is not tied to any resource in particular, so regardless of any new developments in the field we can apply our technology to gain the same environmental and economic benefit and success.

It's very reasonable to imagine many homeowners or businesses with modern heating and cooling appliances to adopt our system of climate control. At a price of a single installment of a few hundred dollars per room and even less once the system is produced by well-organized manufacturing, the DCC could be an international standard in terms of how HVAC works. While the project is sharply focused on reducing energy for environment reasons, it is necessary to have such traits which support its commercial success in order to entice the general public to invest in it. Regardless of an individual's environmental consciousness, the economic incentive alone for installing the DCC suggests that it will be sustainable for long-term development. With such commercial success, we can expand our user-base to contain a large demographic of people who are solely interested in saving money. With this in mind, it's important to note that the product will be more successful in countries and regions which are developed enough to support modern heating and cooling in homes as well as in corporate spaces. This is already a large demographic, and as more regions develop socio-economically, their homes and businesses can be fitted from the start to take advantage of the DCC.

Unfortunately, there are some security and ethical issues related to our project and its implementation. This boils down to two areas specifically: the RGBDT image feed, and the system's connectivity.

The DCC requires the use of several image feeds to train its machine learning model and determine the temperature of the room as well as the people occupying the space. This could be seen as an invasion of our client's privacy if they don't trust the handling of this video data. This issue should not be a cause for too much concern, because video cameras have become common in many household items such as smartphones, laptops, security systems, baby monitors, and video game consoles. We will not actually be uploading any of the actual image or video data to our servers, but we must be very conscious of cyber attacks on our customers privacy to prevent this measure.

Regarding the security of our device, we will have to worry about malware our the network. The need for connectivity between multiple SOC's as well as reporting information and performing diagnostics on our system means that it will be connected to the internet, at least on a periodic basis. Reducing the time the system is connected to the network will help prevent against malware, so a periodic transfer of data and updates using a highly secure encryption method would make the DCC resistant to attacks. This periodic upload would also not be very time sensitive, meaning slower but more secure methods of data transfer over the network would be possible. In addition to third-party security threats, it's also important to acknowledge that the owner of a system may attempt to abuse the data being collected by the DCC. We don’t want users to collect video footage of guests or employees using the system, and therefore must keep the device itself secure from data collection by any users besides our own infrastructure. This means that users should be able to configure temperatures they prefer and other preference based settings, but not have access to changing source code or making hardware modifications.

Summary

The DCC aims to promote more efficient energy use on a global scale through a design that is efficient, secure, and applicable to many different environments and technologies that make it sustainable for use in both the present day as well as many years into the future. As local thermal control means improve, the DCC will remain effective by providing the information and configurability needed to make users happy while saving money and energy in the process. The DCC’s attractiveness to a large demographic of users and applications suggests that it’s commercial success will allow it to be profitable while blazing the trail for efficient climate control and sustainable energy technology for the future.

Technical Discussion and R&D Plan

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Innovation

The main faults of traditional HVAC systems include maintaining a comfortable temperature when many people are occupying a room, as well as properly saving energy when a room is not occupied. Automated air conditioning or heating systems often have a noticeable delay when maintaining temperature when a large group of people enter a room. This is because the system uses thermostats to monitor room temperature, which take time to indicate that there has been a noticeable change to the temperature of the room where the thermostat lies. This means that, for example, a uncomfortably warm temperature being experienced by a group of people may go undetected by a thermostat across the room. Additionally, the system will always try to maintain the the set room temperature regardless if people are or aren't occupying the room. In order to save energy when not in a room or building, the thermostat has to be manually changed or adjusted on a timer (cold during the day, warm at night, etc). It's a major inconvenience to manually change the thermostat each time a person leaves and enters a room.

The result of the stated issues is a waste of money and energy maintaining air conditions in spaces where people don't reside. To solve this, there has been many initiatives in maintaining temperature using local HVAC systems which aim to cool the air around people's bodies. This includes chair coolers, personal desk fans and air conditioning vents, and other devices. While these devices can be effective, they can be expensive to install across an entire office; a single desk cooler may require an infrared temperature sensor, as well as and small personal air conditioning unit. Our project seeks to solve problems of large-scale HVAC systems while avoiding the pitfalls of hyper-local heating and cooling solutions. The DCC scans a room using a single thermal sensor and RGBD camera and counts the number of people present, and where they are situated. This data can be used to automatically turn on/off central large-scale HVAC systems as well as determine the air temperature to be blown into the room depending on whether the room is empty, full, or anything in between. It can also be paired with local solutions as well; because some general location data is provided about the occupants, a local heating or cooling system can maintain the temperature in an area without having to dedicate another set of sensors to one location.

The DCC is also unique in terms of pure academic value. Little research has been done as to whether or not it is effective to combine thermal and color images in trying to detect humans. This has been done separately before, but the two types of images have pros and cons which will be complemented by each other, especially in real-time use. Thermal images can detect human shaped objects quickly, and naturally filter out a lot less non-human noise than color images because the amount of heat humans generate generally distinguishes them more from their surroundings than the clothes they wear or their skin tone. However, color imaging is much better at detecting when humans are crossing paths because they have have the ability to distinguish between fine-details of alike appearances. They're also more reliable in that thermal imaging suffers from issues due to black-white and hot-cold polarity changes, and differences in sensitivity based on the season and temperature of what's in the background of the image.

A constraint that we face, and have put on ourselves, is to make our implementation of such a device affordable and space-conscious. The main processing unit is an UP squared board, which is modestly powered Windows machine. We understand that our system could not be powered by a super computer if it is to be placed in the corner of someone's bedroom or in several office spaces in the same building. Additionally, the thermal sensor we are using, the FLIR Lepton 3, does not have a wide enough field of view such that it could view an entire room in one position. This is because thermal sensors with larger fields of view are significantly more expensive.

These constraints present some added difficulty to our implementation. In order to capture the entire room using the thermal camera, we have assembled a motor controlled bracket which will be adjusted to take multiple images which will be stitched together to create a panorama of the room. Stitching the images is a formidable problem because subjects that move in the scene may be confused as different people in the panorama. Additionally, the UP board restrains the DCC from taking advantage of more computationally-heavy machine learning algorithms. This means the DCC will require an algorithm fast enough to be run real-time on a modest machine. Success in these areas will prove the DCC to be major development in both Computer Vision research as well as a product in the HVAC market.

Key Initial Objectives

There are a number of questions that must be answered during phase I of our research. On the technical side, our product must be able to accurately determine the distribution of heat and people in a room. One of the most important questions to be answered here is "How large of a room can our system cover?" and "At what point would having multiple systems provide better results." We need to know what the limitations of our setup are, and what the best way to improve those aspects would be. The Kinect has a wide field of view, but can only detect depth reliably until around eight meters. This can be adjusted using our own code, but will still be limiting compared to the Lepton thermal camera. Also, some questions this brings up are "How much does depth impact our people detection?" and "Are RGB and thermal frames sufficient in getting the data that we need?" Combining thermal, RGB, and depth images for people detection is something that has not been studied or researched much in depth. For certain situations, it may be fine to purely use RGB data, but for others, it may absolutely necessary to use all of the features.

Another technical topic that may cause an issue is "stitching" together multiple frames so that we can have a full view of the room, as our cameras may not get the full field of view every time. In a basic form, this is very doable. OpenCV, a computer vision library we are using, has a "panorama stitching" function that allows us to do just that. The issue we will encounter is not related to the software, but the time between getting each frame. We will be using a pan/tilt bracket controlled by servos to move the cameras, and capture each frame sequentially. An essential aspect of DCC is being able to identify the number and position of people in a room. To do this, we need a snapshot in time of the room. With what will probably be multiple seconds of time to capture the entire room panning and tilting the cameras, there is a high likelihood that there will be significant movement between frames. That means that one person could be in two or more frames by the end of the frame collection. Someone could be moving in between frames as well. This brings us a new question, “What is the best way to account for time between frames when trying to capture as quickly as possible.” Going back to the topic earlier, the range of the setup may not be far enough to need that many frames to stitch together. Thus the margin for ever would be smaller. We need to figure out if a better solution is possible or even needed for the way our system is planned currently.

The most pertinent question for DCC commercially is how much value the product provides compared to its price. With a mass production of our system, it should cost somewhere between $400 and $500. For an environment like a conference room this should be effective and worthwhile for the consumer, as it should be able to be covered by one system. In a home, however, if DCC was desired for the entire house, at least three systems would be needed. This would not be a reasonable purchase for the average homeowner, especially if it is a house with many small rooms. Because of this we have to ask “If we are planning selling this to homeowners, what kind of home are we marketing to? How large does the home need to be where the value provided by DCC would be significant enough for the consumer to benefit?” It is important that we know what kind of environment our system performs the best in so that we can market it accordingly.

Going back to the question of whether each sensor is necessary, in terms of pricing this is also very important from a commercial point of view. If we discover that we the Kinect does not actually provide very useful information, that is around $100 off of the price of DCC. There may be different combinations of features that work better in different environments. During our first phase of research we have to investigate what situations require which sensors and whether that changes depending on the environment. It’s possible that we should have a “home edition” of DCC that would have a lower cost and have fewer sensors, as it wouldn’t have a need for them.

Technical Milestones

From a technical perspective, we see our project centered around a few key stages of development. The first phase is to get the entire system up and running: this includes building and calibrating the bracket for an adequately sized room and sending appropriate commands, transferring thermal data from the Lepton over the network, and having a basic classification model for the images we are presenting the device. This allows us to collect sample data and decide on a baseline for what learning model we are going to use. Our initial model is a pre-trained SVM which uses images from actors in both sitting and upright positions, as well frontal and profile positions facing the camera. This will be done for both the color and thermal cameras. This way we will be able to compare exactly what the color camera is able to detect well versus the thermal camera.

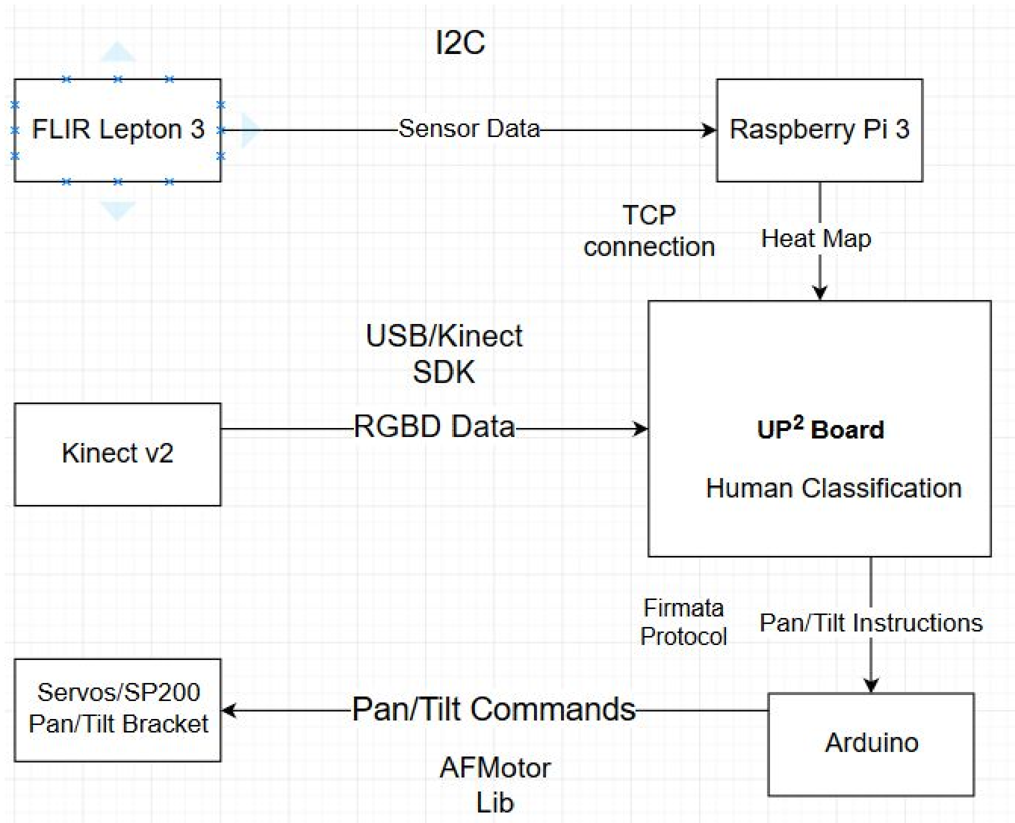
The next phase is having images from the thermal camera properly stitched together and matched geometrically with the color camera. We will have to adjust the resolution of the cameras depending on how many images we need from the thermal camera to get a full field of view of the room. Using the least amount of images necessary is optimal to reduce the amount of time subjects have to move while the motors are changing the position. The closer the images are to the scene when the first frame is captured, the less we will have to worry about correcting inconsistencies from people moving about.

The next stage is primarily focused on the main algorithmic component of our project. This is where the aspects of thermal and color imaging are combined to complement each other. This involves creating feature descriptors for both images and running object detection simultaneously. This will include correcting the problems due to panorama stitching. Currently, our design seeks to create an initial reference frame using the wider FOV color camera and tracking humans using a HOG descriptor and a pre-trained SVM. The reference frame will be used to account for false positives and false negatives from moving humans moving in and out of view from the thermal camera.

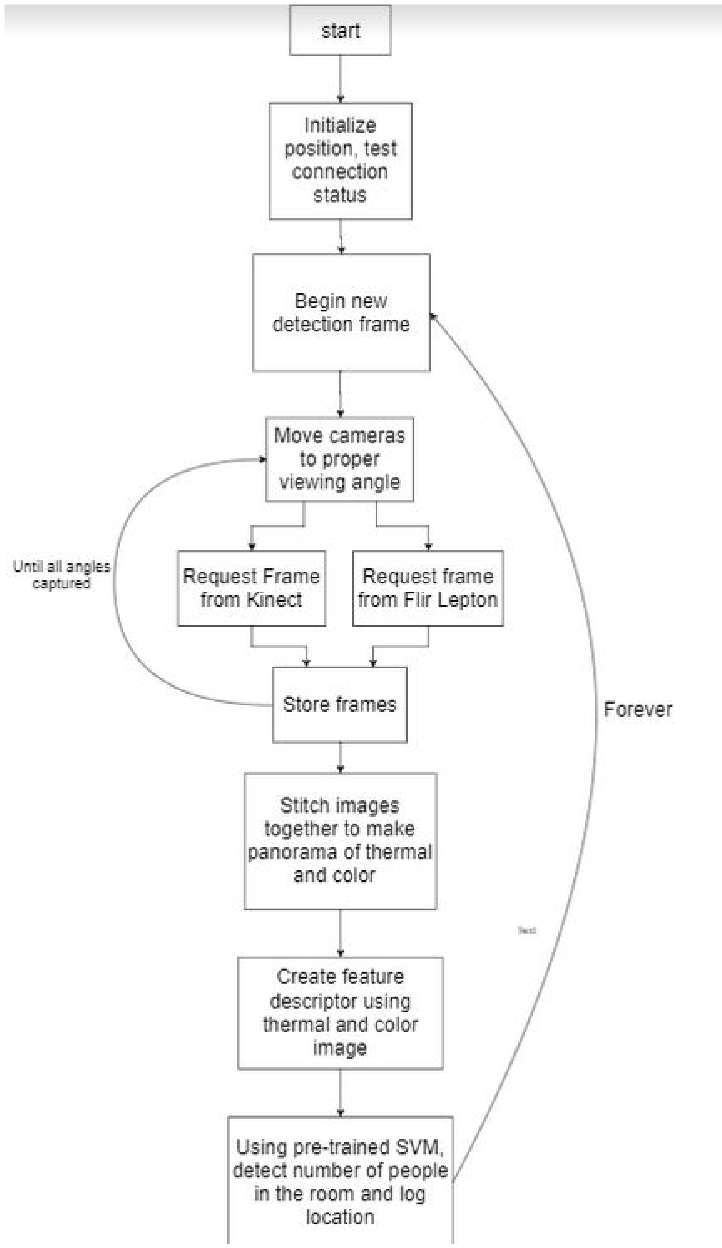
Lastly, depth will be integrated into the algorithm. This involves both detecting skeletons from bodies to differentiate them in crowds, as well as using depth to determine where people are located in the room. The latter will be used to in combination with the actual HVAC vents to pinpoint where to cool. While the kinect depth sensor is not very far-reaching, it should be sufficient for use in small rooms and making a functional prototype.

R&D Plan and Timeline

This month, we are working on getting communication between all of our systems running. This means getting communication between the raspberry pi, which is getting information the Lepton thermal camera, and the UP board, which is the centerpiece of our system. Also included is getting commands sent from the UP board to the Arduino, which is controlling the pan/tilt servos. Finally, the UP Board will also be getting frames from the Kinect, as shown below.



Looking forward to January, we are going to be training our SVM using example data we've gathered. Also, we are going to begin working on the stitching of our frames using OpenCV. Another aspect we are moving towards in conjunction with everything else is the main control flow of our program, shown below.



This will be a continually growing and evolving part of our project. Once the other parts are completed in January, we will begin combining the features we have extracted from the stitched image to plug into our SVM.

Continuing into the Spring, we'll be working on refining our SVM and doing additional testing to make sure our findings are correct. We will experiment on different sizes and types of rooms with varying amounts of people. This will hopefully be between April and May.