MBARI Monterey Bay Aquarium Research Institute

Scalable and Sustainable 3D Positioning Systems

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ABSTRACT

3D positioning systems are systems used to position cameras, sensors, or other hardware in 3D space, and are often expensive or hard to repurpose. The purpose of this project is to develop a low-cost, scalable, and sustainable 3D positioning system that can be used as a blueprint or proof-of-concept for similar or more in-depth systems. In this project, this was done by repurposing a 3D printer and communicating with it via a computer and a serial connection, and testing results were collected using a camera and calibration checkerboard. The results from testing this prototype showed that the system was capable of moving with a high level of consistency, a high level of accuracy, and was capable of creating composite images that exhibited marginal levels of jitter and inconsistency. This proves that a scalable and sustainable 3D positioning system has the potential to be a useful and flexible tool that could provide a lot of value to MBARI and other similar institutions.

INTRODUCTION

At MBARI and other similar institutions, there is a high demand for collecting photos, videos, and other forms of data and information about the ocean and natural world. Additionally, due to a variety of reasons and circumstances, it is often necessary that the cameras or sensors collecting the photos, videos, or data, move around in three-dimensional

(3D) space. As such, it can be quite difficult to ensure that the camera or sensor will work properly without first testing it to make sure it is capable of operating and recording while moving throughout 3D space. One example where 3D positioning is considered absolutely critical is the positioning of cameras or sensors being used on an underwater robot, as precise calibration and coordination is often necessary to achieve the necessary positioning and data collection.

As a result of this need, several forms of testing and validation are often used. The first tool that might be used to validate a system such as a camera placed on an underwater robot could be a simulation, where a model of the robot or camera is created within a virtual 3D environment. This typically allows the user to get a rough estimate of how the system will perform when moving and adjusting in 3D space. To reach a better and more complete validation, the next most robust method often involves operating the full-scale system in a scaled down environment. In the case of an underwater robot, this might be something like placing the robot in a test tank (like the one MBARI uses) to validate its movement and data collection capabilities. Although this is the best method for truly getting a sense of the system's capabilities, it is often a difficult, time consuming, or expensive process that requires the full assembly and deployment of the device. The problem in question, then, is that there remains to be developed a tool that can slot somewhere in between these two ranges, providing a tactile testing environment for cameras and sensors in 3D space without requiring an elaborate or fully refined setup or testing plan.

One way to do this would be through the use of a 3D positioning system. 3D positioning systems are devices that use a variety of mechanisms and methods to move a camera, sensor, or other device within 3D space. These devices are found in a wide range of industries and applications, and common iterations of them include robotic arms, CNC machines and routers, 3D printers, laser cutters, cranes, and camera positioning devices such as linear actuators. The main issue that solutions like these presents is that they typically fall into one of two categories: large, high-cost systems that are often used for industrial or extremely high-load applications, or low-cost systems that are usually smaller and have very narrow use cases, like 3D printers and small CNC machines.

It is through the combination of these two problems that the goal of this project becomes clear: to create a prototype version of a multipurpose and scalable 3D positioning system that could be used for a variety of different scenarios. This setup should be more cost effective than existing solutions and should ideally reuse or repurpose existing hardware. It should also allow for the creation of an easy-to-use interface for operators. This would allow MBARI scientists to research topics that study loop closure in controls and imaging, with examples of applications being 3D tracking of animals in a water volume to enable high resolution imaging of biomechanics, laboratory testing of simultaneous localization and mapping (SLAM) algorithms, and structured lighting and hyperspectral imaging (HSI) testing on scaled targets.

MATERIALS AND METHODS

DESIGN REQUIREMENTS

The first part of the design process was composed of outlining the requirements, desired outcomes, and stretch goals of the project. This would set a baseline that would influence design decisions and would help determine if certain approaches would be feasible for the manufacturing and assembly of the final design. The critical part of the design is that the device must be able to utilize dynamic and fluid position control using G-code via python or a similar software interface. Additionally, it should have speeds comparable to a standard 3D printer, somewhere in the range of 25-100 mm/s, with acceptable accelerations and jerks such that it doesn’t negatively impact the camera or sensor being tested. Another key aspect of the design is the volume that can be accessed by the camera or sensor; in this case, the potential for scalability was crucial, with a 100mm cube being the initial target with the hope of increasing up to an order of magnitude greater than that. Finally, it was the hope that the base design could be a created from a machine or parts that were in need of reuse or repurposing, as this would lower the cost of the project and be both easier and more sustainable.

BASE DEVICE SELECTION

After this initial step of deciding on the requirements, a background review on available 3D positioning designs and ideas was performed to find a feasible option that could reasonably be designed around, modified, and tested in the time allotted for the project.

This step of the validation involved narrowing down the scope of the search to a certain type of system: what sort of device would be easy to get ahold of and could be easily modified and interfaced with via a controller or computer? This eliminated several options, including CNC routers, linkage-based systems, and non-linear 3D printing systems, as seen in the figure below (Fig 1).

Positioning System Approach	**Typical Speeds (XY)**	**Typical Speeds (Z)**	**Volume**	**Standard Weight of extrusion head/etc.**	**Design Limitations**	**Cost**
Cartesian Printer system	25-250 mm/s (hardware dependent)	Typically power screw (25-40 mm/s)	150+ mm cube	350-700g	Slow z-axis movement, less precise movements (more vibrations/etc.)	$100+
CoreXY/H-bot printer system	Much faster (250 mm/s+)	Typically power screw (25-40 mm/s)	~100 mm cube	100-300g	Belt based, expensive, slow z-axis movement, less massive print head	$300+
Delta printer system	150-600 mm/s		Cylindrical volume	100-300g	Hard to modify for our purposes, limited volume	$300+
SCARA/linkage-based systems	100-200 mm/s	Power screw	Cylindrical volume	100-200g	Less precision, more obscure	$300+
CNC router	40 to 100 mm/s XY	N/A	100x100x40mm		Much harder to modify	$800+

Figure 1: Table Comparing Attributes of Different Positioning System Approaches

Using this chart, it was established that a Cartesian or CoreXY 3D printer would be the best option, based upon factors such as cost and sustainability. It was determined that a 3D printer provided by Paul Roberts that he had been using personally and had just replaced would be the baseplate upon which the project would be built. This machine was a Creality Ender-3 3D Printer (Fig 2) and ran via an XZ-head system where the X-axis ran off of a belt drive and the Z-axis ran off of one power screw, while the Y-axis was isolated from the other two to move the build plate, also running off of a belt drive. (Fig 3).

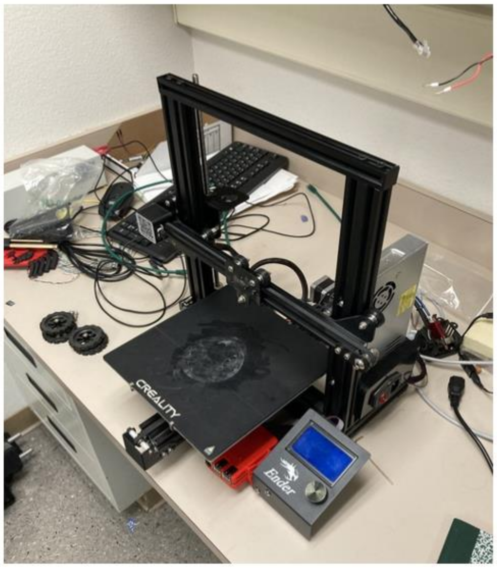

Figure 2: Creality Ender-3 3D Printer (extruder head and filament drive removed)

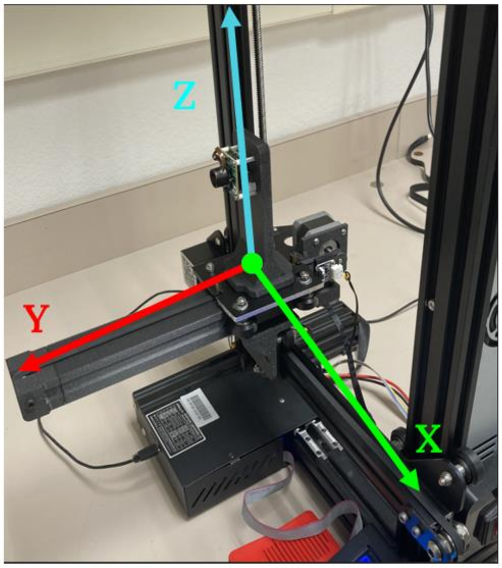

Figure 3: Annotated picture of the modified device showing the X, Y, and Z directions)

DESIGN/MANUFACTURING

The first steps to the manufacturing phase of the device were to disassemble the stock 3D printer and remove everything that would not be necessary for the use it would be serving. This included the extruder head and filament drive, heating elements, build plate, extra cables, and any other unnecessary hardware.

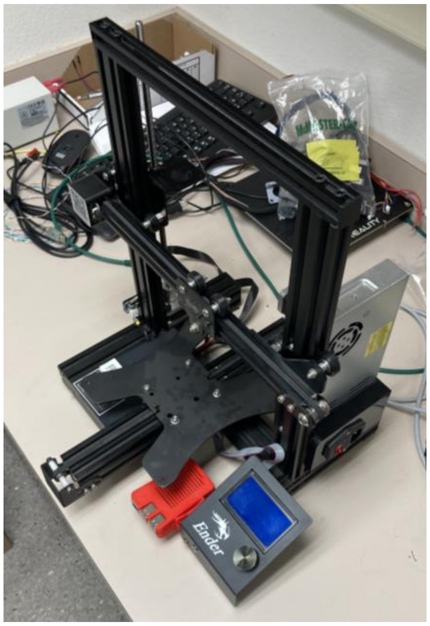

Figure 4: Picture showing 3D printer disassembled with all unnecessary hardware removed

One of the main limitations of the base 3D printer which made it initially unsuitable for this project's needs is the fact that the Y-axis motion is separate from the X and Z axes, as it was initially used to move the build plate separately from the X and Z motion of the extruder head. Given that the end goal of this project is to create a prototype that can move a camera or sensor fluidly around 3D space, it is necessary that the 3rd axis of motion be attached to the other two, meaning that a redesign of the 3D printer is necessary.

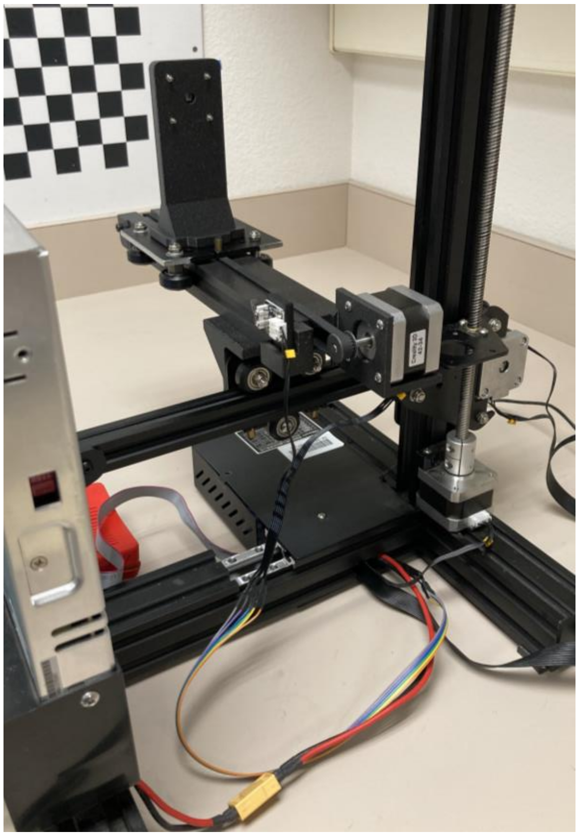

Figure 5: 3D printer redesign

Since the power screw that controls Z-axis motion is fairly low-powered and not self-locking, it became crucial to come up with a different solution than simply attaching the Y-axis belt drive mechanism to the plate that the extruder was attached to. However, because the plate that was attached to the Y-axis belt drive made for a convenient mounting point for sensors and cameras and had compatibility with the belt drive and fixtures of the printer, the final design included this rolling plate attached to a 3D printed T-slot rail (similar to the 80/20 aluminum extrusion that the original printer had used). However, this required taking the plate to the MBARI machine shop to trim it down to the required size, cutting the timing belt to length, and creating custom fixtures that would suit the required geometry of the design and the requirements established at the beginning of the project (see below). Additionally, lengthening the cable that ran from the board of the printer to the Y-axis stepper motor was necessary to make sure that the design had the full range of motion, as the Y-axis had to move with both the X and Z axes.

RAPID PROTOTYPING/3D PRINTING

One of the primary technologies that was used for the manufacturing of this prototype design was FDM 3D printing using a Prusa MK4 3D printer owned by the CoMPAS lab. Using Solidworks (a 3D modeling CAD software that allows for the generation of very specific and precise geometry), models of a variety of custom fixtures could be generated. These models were then converted into .STL files and fed into the Prusa slicing software, a tool that adjusts the settings of the model and prepares instructions to give to the printer for the part. Then, the instructions were put on a USB flash drive, given to the printer, and the part could then be created, with the whole process taking between 30 minutes and several hours, depending on the size and complexity of the part. This is a process known as "rapid prototyping", and it served as an incredibly useful tool for this project.

Figure 6: 3D printed parts created during the project

One of the main upsides of rapid prototyping in this case is the quick turnaround time on highly customizable parts, as several iterations of a part were often needed as tweaks were made and slight modifications or new discoveries about the needs of the final design became known. By being able to adjust a model slightly, create a new set of instructions, and start printing a new part in a matter of minutes, the iterative design process was able to move towards a final design much faster than through other manufacturing processes. Furthermore, the process is incredibly cost effective, with the Prusa slicing software estimating that the entire process cost about $16.44. This cost accounts for the total amount of PLA filament used in the process. Finally, the ability to generate parts of very precise geometries was invaluable to this process, as it allowed for dovetailing and other methods of joinery to be implemented into the parts, giving them the ability to be quickly and frequently be assembled and disassembled when testing and reconfiguring the prototype.

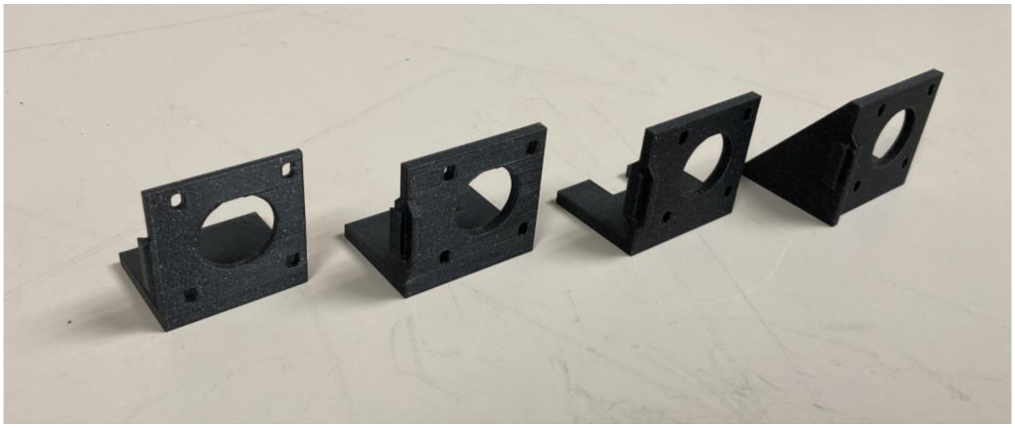

Figure 7: Example of iterative process and dovetailing technique

COMMUNICATION/POSITIONING

For communicating with the prototype, it was determined that a serial connection using a USB 3.0 to Micro USB cable would be the best way to utilize the built-in hardware and software on board the Creality printer. Initially, testing was done using OctoPrint, an open-source 3D printing project that gives users control of their printer in a more hands-on way than is usually available. Through OctoPrint, testing was done via some of the built-in controls as well as the control terminal to test the speeds, accelerations, and overall agility of the printer. This was also where testing of manual input of G-code commands as a way to move the printer from point to point was initially done. G-code is a software that is used on many different types of 3D positioning systems, such as printers, routers, CNC milling and cutting machines, and many others, and it essentially works by creating a file of instructions that a positioning system (like a printer) can execute one by one until the file is complete. The relevance of these commands range from machine to machine but some examples that relate to a 3D printer are to move to a certain position, change velocity, change the temperature of the extruder, change the extrusion rate, wait for an amount of time, change coordinate systems, and many more.

For the initial testing, the commands that were used manually were primarily to move to certain positions, change velocities, and change/update the local coordinate system. The next step in the testing process involved using TeraTerm, which is a free and open source software that can be used to access different terminals on the computer. When the baud rate and settings were adjusted properly, this allowed for (essentially) direct access and communication with the prototype. Through TeraTerm, more conclusive testing was done, and the experimentation and data collection was completed, as more complicated instructions and even basic scripts could be run. However, this is far from a permanent solution, as it requires a lot of manual input, knowledge of specific G-code commands, and time to get set up with each testing session.

For future use, it is recommend that Python (or another similar language) is used to create a more abstracted and easy-to-use controller. If time had allowed, the plan for this project was to create a prototype controller using Python, as there is a package called PySerial that allows for communication between the computer and the controller via a serial port, similar to TeraTerm. Through this, a UI could be created that could have built in inputs, scripts, and sequences that could be used to configure, calibrate, or test a number of different setups depending on how the positioning system was arranged.

FINAL DESIGN

The final design (seen below) features timing belt drives for the X/Y axes and a power screw for movements along the Z axis, which are features carried over from the base 3D printer. The system is capable of moving at ~6500 millimeters per minute, or ~4 inches per second, in the X and Y directions, and is capable of moving at 2000 millimeters per minute, or ~1.5 inches per second, in the Z direction. Both of these velocities are increases over the printer's previous capacity, as running the motors via manual commands enables higher speeds and accelerations without risk of damaging the hardware. To enable smooth and simultaneous movement in all three directions, the Y-axis (which holds the plate that the sensors are mounted to) is mounted on a platform that moves along the X-axis, and the X-axis is controlled by the power screw that controls the Z-axis. The system's total volume was approximately 140mm x 120 mm x 180mm (X/Y/Z), and for testing purposes a volume of 100mm x 100mm x 100mm was used. This volume could be easily expanded by simply increasing the axis and belt lengths, creating a more functional and useable device outside of a testing/validation setting.

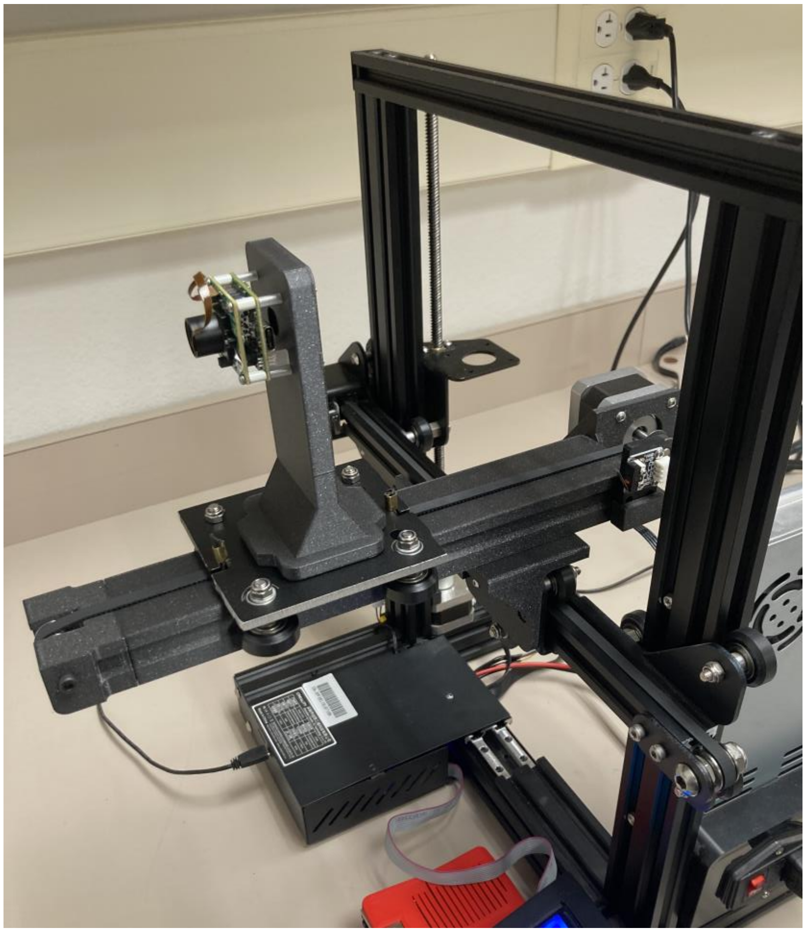

Figure 8: Final design configuration

TESTING PLAN

To test the system, a small camera was mounted to a fixture that was then mounted to the plate on the Y-axis. This camera would take pictures and videos that could then be used to analyze the quality and consistency of the movements done by the prototype. The subject of these images and videos would be a checkerboard, meaning that if the size of the boxes on the checkerboard is known, the consistency of images and videos can be easily checked.

The first test that would be done is known as “out-and-back” testing. This process is done by starting the sensor at a known “origin” location (0,0,0) and moving it out a set distance in each of the 3 directions to a point (X,Y,Z). An image was then captured and saved, and the sensor was moved back to the origin point (0,0,0). The camera was then moved again to the same point as before (X,Y,Z) and another image was captured and saved before returning to the origin location again. This process was repeated five times to capture five total images per test, and the test was performed at three locations of increasing distance from the origin. To process these photos and determine the consistency of the positioning systems movements, image subtraction was conducted. This is a process by which the images were stacked on top of each other and the pixel values were subtracted, showing the differences between two different images (seen below). These data sets can then be analyzed to quantitatively and qualitatively show the ability of the positioning system to move accurately and consistency via statistics like max RMS error, pixel shift, and distance between images.

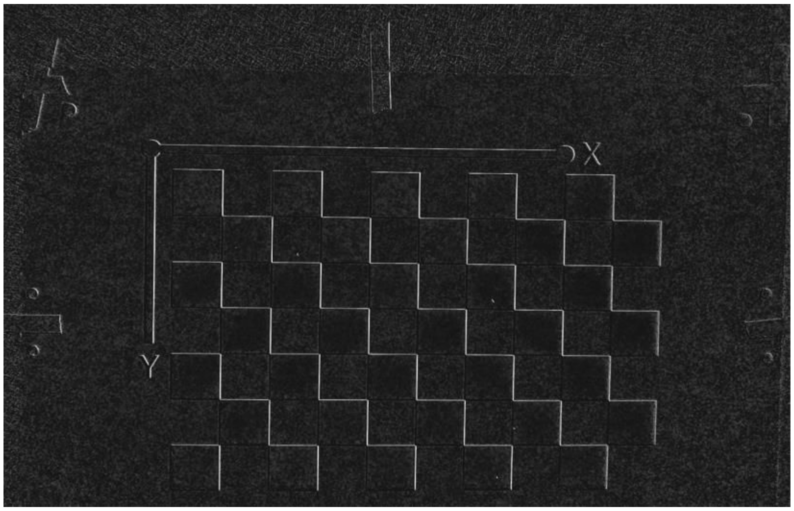

Figure 9: Image subtraction example

The second method of testing used is a method known as push-broom image creation, because of the methods similarity to a wide “push broom” being pushed across a surface. This is a method during which the camera is moved along one of the axes parallel to the checkerboard (in this case, the X and Z axes) at a constant speed while taking a video. From each frame of the video, the same column of pixels is taken, and the columns of pixels are then placed next to each other to create a composite image. This method of testing shows the jitter and consistency of the movements done by the prototype during the run.

RESULTS

CONSISTENCY TESTING

The results relating to the consistency of the out-and-back testing are seen below. Three points were chosen for the data collection, each at 25-millimeter intervals in each direction from the origin point. As can be seen from the results, in each set the max RMS error between images was less than 1%, giving a qualitative overall feel of the consistency between the images and indicating a very low variance and very high consistency at each distance.

Distance (mm)	**Max RMS Error (%)**
25	0.79
50	0.79
75	0.66

Figure 10: Consistency testing results

ACCURACY TESTING

The results indicating the accuracy of the out-and-back testing are seen below. Across the same three data sets as above, the maximum shift between the edges of squares on the checkerboard across all of the images was measured after the images had been enhanced by a factor of five, giving a general sense of the specific accuracy across the sample set. At each of the 3 distances, the maximum edge shift was determined to be a sub-pixel shift of approximately 0.5 pixels (in the original image). This can be measured using the distance of the squares to the camera to be less than a quarter of a millimeter in each case, indicating an extremely high accuracy in these cases.

Distance (mm)	Max Edge Shift (Pixels)	Max Pixel Shift (mm)
25	0.5	0.16
50	0.5	0.15
75	0.5	0.14

Figure 11: Accuracy testing results

COMPOSITE IMAGE CREATION

Seen below is an example of an image taken from one of the videos taken during the push-broom testing compared to the composite image created from that same testing run, with the image on the left being a standard image taken of the checkerboard and the image on the right being a composite image created by stacking columns of pixels next to one another.

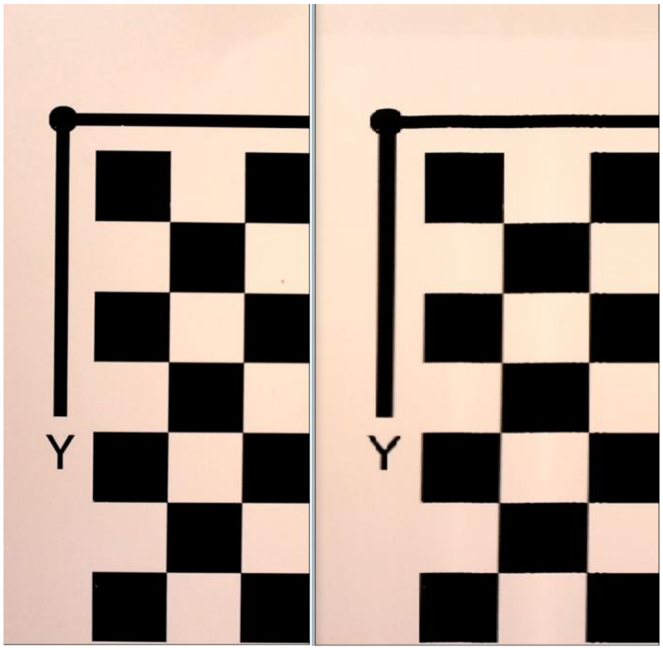

Figure 12: Composite image creation example

As can be seen in Figure 12, there is almost no discernable difference between the two, indicating that the prototype moves in a very consistent and uniform manner. If examined closely, there is some slight jitter at some points, but the overall quality of the composite image is very high in this regard. Additionally, the uniform size/spacing of the checkerboard squares indicates that the positioning system is moving at a uniform speed.

DISCUSSION

Overall, the results seen from the testing done with the prototype 3D positioning system reflect quite positively on the project as a whole. As can be seen from the consistency testing, the prototype is capable of arriving at the same position consistently with less than 1% error overall at a range of distances. The encouraging part about this testing is that increasing distance had no effect on the capability of the positioning system to remain consistent in its motion, meaning that scaling up the size of the axes and increasing the volume with which the sensor is capable of covering should have no effect on the consistency at which the sensor can be moved.

Furthermore, the results of the accuracy testing are also extremely encouraging. The edge shift was the same at all three distances of testing, meaning that there was no issue moving accurately to any of the points, independent of the distance between the point and the origin. This is encouraging, as it means calibration sequences and tests that need to be carried out with a high degree of accuracy on cameras, laser generators, or other sensors will be able to be done on a device similar to this sort of design on a scale larger than was used for this prototype.

Finally, the composite image generation tests also yielded beneficial and overall positive outcomes. The important takeaways from the creation of these images was that the movement of the camera was smooth and consistent and that there was minimal jitter along the axis perpendicular to the movement of the camera. As can be seen in Figure 13 below, which is an enhanced version of Figure 12, there is a very slight sign of this vertical jitter of the camera. This is due to the cantilevered nature of the Y-axis, and is something that can be fixed and likely eliminated entirely with slight changes to the design of the positioning system.

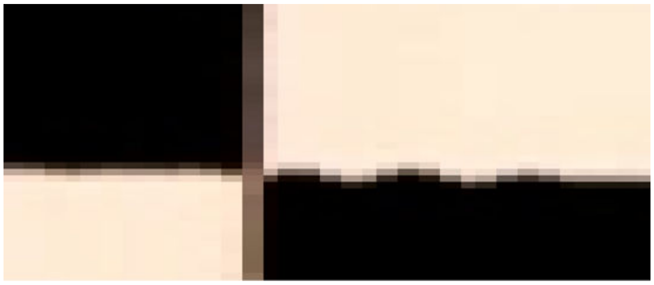

Figure 13: Enhanced composite image to show jitter

CONCLUSIONS/RECOMMENDATIONS

CONCLUSION

In conclusion, this prototype serves as a useful platform for future expansions on the idea of a multipurpose and scalable 3D positioning system. The design was proven to be consistent and accurate in its movements and is capable of providing the smooth movements necessary for calibrating and testing sensors while accelerating and moving that would make it a useful laboratory tool; additionally, it provides a scalable platform that enables for increasing the overall volume the positioning system is able to cover with minor changes to the design. This means that the concept could be useful as a starting point for a testing tool that could be used with equipment like cameras, sensors, lasers, and other devices, or as a standalone tool that could be used alongside a laboratory setup for something like tracking the biomechanics of an animal.

DESIGN IMPROVEMENTS

To increase the overall useability of the 3D Positioning System as a device and as a concept, the following suggestions are made about improving the design. Primarily, it is recommended that the Y-axis be designed to be less cantilevered and more supported, as this would remedy the slight jitter seen in the composite image creation testing when moving along the X-axis while at the end of the Y-axis. This could be done by adding another power screw or drive to that end of the axis, or by moving the Y-axis to make it more centered on the X-axis platform. It could also be done by using stronger, stiffer, or lighter materials once the design has been fully developed. These stronger materials and increased support would also help the positioning system better accommodate more massive sensors, as it is currently quite limited in this capacity (testing was done with a total sensor payload of 60g, or ~2 oz).

Additionally, another feature that could greatly increase the useability of the device would be to add several interchangeable configurations specific to the use cases that the positioning system would be used for. This could include things like different platforms/mounting points for sensors and support arranged in different ways depending on the weight/size of the sensor being used. This interchangeable hardware would allow for quickly changing from one setup to the next, decreasing downtime and maximizing the use cases accessible by the positioning system.

Finally, another design improvement would involve changing the design slightly to allow for more axial flexibility with the directionality of the sensors. With a larger useable volume and less obstructions around the outside of the volume, sensors could be pointed in different directions than the very limited options that were available in the current design. This would allow the positioning system to be placed in an environment that could be changed to suit the needs of the current use case in a more flexible manner, although having the option to move the device around would still be a valuable feature to have.

FEATURE RECOMMENDATIONS

The following are some recommendations for features that could be added to the positioning system as it becomes a more fully fledged entity. First, making the blueprints and software used in operating it open-source could be a useful possibility, as this project is meant to be a step forward in the space of 3D positioning systems, and making the software, testing plans, layouts, or other code available for others to use and improve on could be valuable. Additionally, adding customizable layouts that can be easily switched between would be a good step once the hardware has been developed, as this will cut down on the time and energy necessary to switch from one setup to the next. Finally, an intuitive UI or GUI to control and test the system made via Python or other similar software would make the system user friendly and easy to work with, making the positioning system more accessible.

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