How to make a Motorized Linear Translation Stage

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Abstract

Motion stages allow controlled, precise, and repeatable motion in a single degree of freedom. A variety of different stages are available on the market which allow linear translation, rotation, tilt, and even multi-axis motion. In this tutorial we will concentrate on building a motorized *linear* translation stage. Purchasing ready-made motorized linear stages can be very expensive, for instance a linear translation stage allowing 12 mm of travel in one direction with a stepper motor can cost between $1500 to $2000 from Thorlabs [1]. Below we outline a cost effective way to build a motorized linear translation stage.

Introduction

A linear stage is used to allow motion along one degree of freedom and to constrain all other degrees of motion. Linear stages can allow rotation about roll, pitch, and yaw angles or translation along x, y, and z axis [2]. A linear motion stage consists of the following parts:

1). Linear stage or carriage
2). Rails
3). Stepper driver
4). Stepper motor with linear actuator
5). Opto-interrupter
6). Lab power supply

The resolution of the stage is quantified by the step size of the stepper motor and the repeatability is driven by how much friction is present between the rail bearings and the carriage. Repeatability and resolution are also driven by how accurately the motor responds to commands. It is important that the stage and rails are able to withstand the wait of the instrument that you want to move, with out deforming otherwise the performance of the ball bearings and the length of the translation stage will be affected. Proper locking mechanism for the stage needs to be in place to give the linear stage stability. To avoid driving the linear actuator clear out of the stepper motor or to avoid driving the instrument off the stage proper calibration of step size to linear translation needs to be performed at the beginning to the experiment.

Linear Sage and Slide

The linear stage is what the instrument (camera, membrane, or mirror) that we want to move, sits one. It consists of one or more slides sandwiched between two metal plates. The instrument is bolted on to the top plate, which is free to move with the slides. The bottom plate is locked to the optical bench. The lead actuator bores into the top metal plate producing the translation.

The slides plus the flat metal plates should be able to withstand the weight of the instrument without deforming. Therefore a material with high specific stiffness should be used. The metal plates should be wide enough to comfortably span the breadth of he instrument. For large instruments two slides can be used to lend stability. The two rails can then be appropriately positioned on the metal plates to allow smooth translation.

The performance of a translation stage is determined by the type of bearings used. There are a variety of different types of rails or slides, four major types of slides are dovetail slides, ball bearing slides, crossed roller bearings, and flexure suspension [2].

Dovetail slides are the simplest type linear translation slides. They consist of two flat surfaces sliding against each other with the geometry shown in figure 1(a). Dovetail slides have relatively high stiffness and load capacity. They are resistant to shock and fairly immune to contamination. The friction of dovetail slides varies with translation speed, which makes precise control difficult and limits the resolution of the stage.

Ball bearing slides reduce friction by replacing sliding motion with rolling motion. In this arrangement the balls are allowed to slide back and forth against steel rods known as guides ways (Figure 1 (b)). The friction between the ball bearings and guide ways is very low resulting in smooth travel with the capability to make small controlled movements. The ball bearings make contact with the guide ways at a single location allowing the dirt to be pushed out instead of getting trapped. This makes the ball bearing slides relatively insensitive to contamination.

Crossed roller bearings replace the point contact of ball bearings with the line contact of a roller. This leads to higher load capacity and higher stiffness. Crossed roller bearings require more care during assembly resulting in higher costs and are thus reserved for applications that require the greatest stability, stiffness, and robustness.

Flexures use elastic deformation to control motion (Figure 1 (d)). Since there is no sliding or rolling contact between the moving parts of the stage, friction is completely eliminated. Flexure suspension allows higher stiffness and higher load capacity. The disadvantages of flexures are smaller range of travel, susceptibility to vibration, and a small amount of cross coupling between axes.

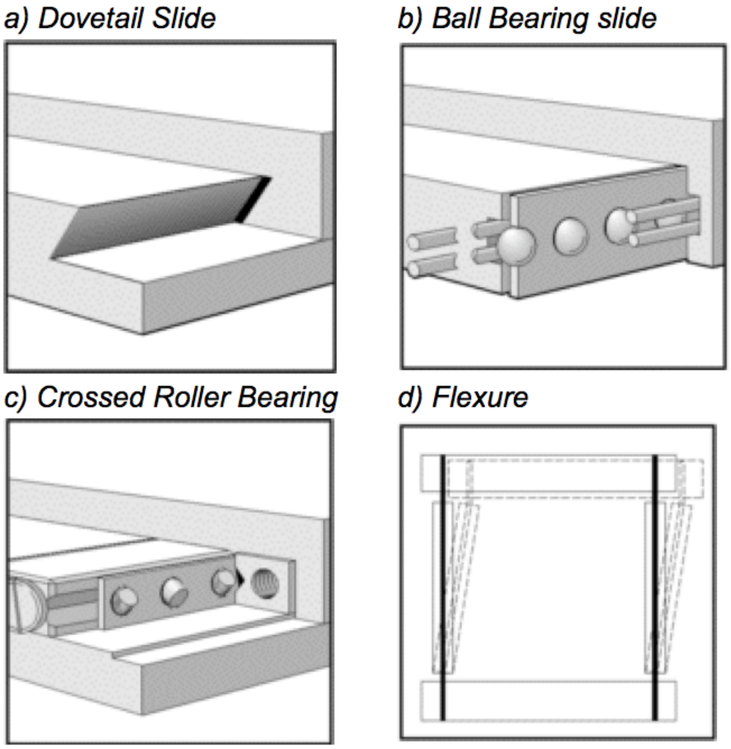


Figure 1. Four different types of slides are shown, a) Dovetail slide, b) Ball bearing slide, c) Crossed roller bearing, and d) Flexure [2].

Stepper Motor Based linear actuator

A stepper motor operates by converting rotary motion to linear motion. Stepper motors move a given amount of rotary motion for each electrical impulse. Current stepper motors on the market can obtain resolutions from 18 rotational degrees per step to 0.9 rotational degrees per step. Permanent magnet stepper motors incorporate a permanent magnet rotor, coil windings, and a steel stator capable of carrying a magnetic flux. Energizing the coil creates a magnetic flux as shown in Figure 2. The stator conducts the magnetic field and causes the permanent magnet rotor to be aligned to the magnetic field. The stator magnetic field can be altered by sequentially energizing and de-energizing the stator coil. This causes a stepping action and incrementally moves the rotor resulting in angular motion. A one-phase stepping sequence is depicted in Figure 3 [3].

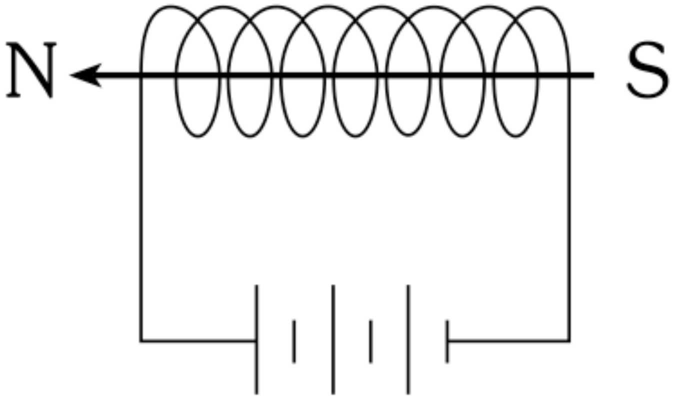


Figure 2. A north to south magnet field is created and magnetic flux is generated in the coil [3].

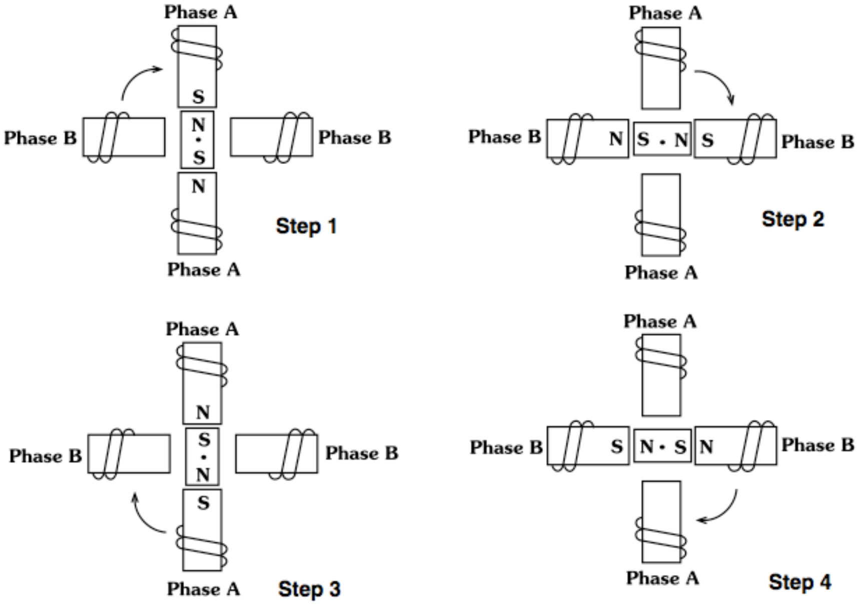


Figure 3. Illustrates the step sequence for a 2-phase motor. In step 1 phase A of the 2 step stator is energized. This magnetically locks the rotor in the position shown since opposite magnetic poles attract. When phase A is turned off and phase B is turned on the rotor moves 90° clockwise. In step 3 phase B is turned off and phase A is turned on with the polarity reversed from step 1. This causes another 90° rotation. In step 4 phase A is turned off and phase B is turned on with the polarity reversed from step 2. Repeating this sequence causes the rotor to rotate in 90° increments [3].

A linear actuator produces a linear translation. Inside the rotor there is a threaded precision nut with a lead screw. The lead screw in turn is fixed to the translation stage with a nut. As the rotor turns linear motion is achieved directly through the nut and threaded screw. The size of the leadscrew depends on the range of translation required. The precision of the motion depends on the step size of the stepper motor and on the coupling between the motor and lead screw. The threads of the lead screw allow a small rotational force to translate into a large load capability depending on the steepness of the ramp, which is a function of the lead, pitch, and diameter of the screw. A small lead (more threads per inch) will provide a high force and resolution output. A large lead (fewer threads) will provide a lower force, but correspondingly higher linear speed. An example of different lead configurations is shown in Figure 4 [4].

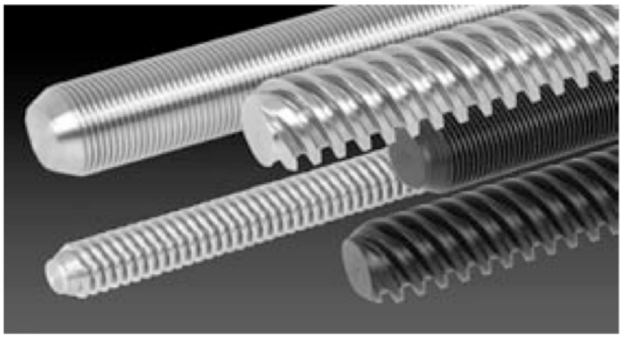


Figure 4. Four different leadscrews showing four different leads [4].

In choosing a rotor plus leadscrew you need to consider how much torque/force is required? What is the duty cycle, desired step increment, step rate, and max translation range. Bipolar or unipolar coils are selected depending on whether or not dual directional motion is needed)? We also need to consider life expectancy requirement and environmental constraints. A stepper driver is used to drive the stepper motor and linear actuator.

Apparatus and Assembly

In this section we construct a motorized linear stage for a specific application listing the particular parts, where to purchase them, and how to assemble the parts to have an operational motorized linear translation stage. We list all the parts needed and where they can be purchased in Table 1.

Part	Part Number	Quantity	Part Description	Vendor	Cost
Aluminum block	N/A	1	20 x 100 x 200 mm plates to form the base and top of the translation stage. 90° Corner Plate (100 mm in length) to mount additional components	Aluminum block found in lab and cut in the machine shop. Can also be purchased from McMaster-Carr.	$0
Telescopic ball bearing slides	8379K1	2	76 mm stroke length.	McMaster-Carr	$90.89/each
Stepper motor + leadscrew	28F49-05-023ENG	1	Non-captive, series 28000, size 11 with 4 in leadscrew.	Haydon Kerk	$120.88
Stepper driver Kit	EZHR17ENSK	1	1 EZHR17EN stepper motor controller + driver. 1 RS485 converter. 1 opto-interrupter.	All Motion	$225
Hex nut	932827A225	1	Used to bolt the leadscrew to the translation stage	McMaster-Carr	$11.55/pack of 100.
Socket cap screw	92196A533	4	¼-20. Used to bolt aluminum posts to the aluminum base plate.	McMaster-Carr	$3.53 / pack of 25.
Socket cap screw	92196A619	4	3/8-16. Used to bolt the slides to the aluminum base plate.	McMaster-Carr	$6.95 /pack of 10.
Set screws	91375A33	6	¼-20 cup.	McMaster-Carr	$11 / pack of $100.
Posts	NT59-754	6	3 in posts with ¼-20 stud at the top and ¼-20 tapped threaded hole at bottom.	Edmund Optics.	$9.75/post
Power Supply	Instek PST-3201	1	Lab power supply	Tequipment	$873

Table 1. List of the apparatus needed to build and drive a linear translation stage.

The application is to move and Andor iXon camera through a distance of about 60 to 70 mm in 1.5 mm increments. The camera weights 4.5 kg (~10 lbs). There is no hard-set constraint on the speed with which to move the camera. From these requirements we can determine the size of the lead screw, the power of the stepper motor, and the step size or resolution needed. The following formula can be used to determine the power of the motor [3]:

$\text{Power}_{\text{linear}}$ (watts) = [distance travelled (m)* force (N)] / [time taken (sec)]

Several options of motors based on frame sizes and power are available from the vendor Haydon Kerk. Figure 5 shows plot of force vs. speed provided by the vendor. This plot is very helpful in choosing the correct motor for your application.

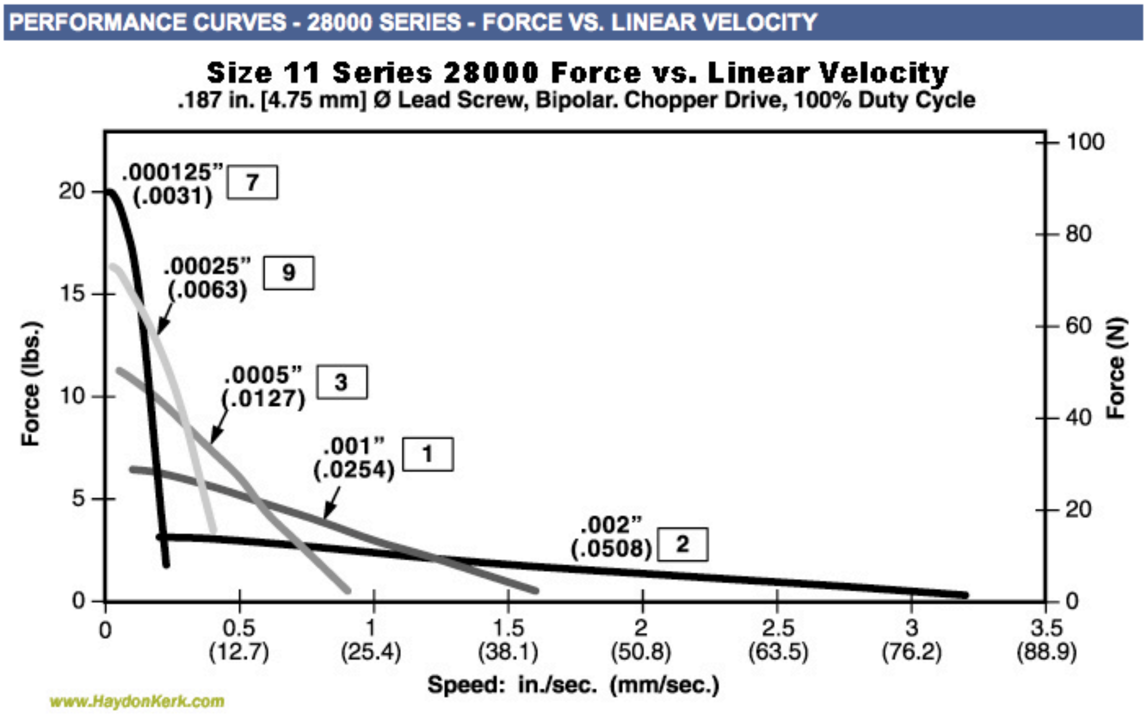
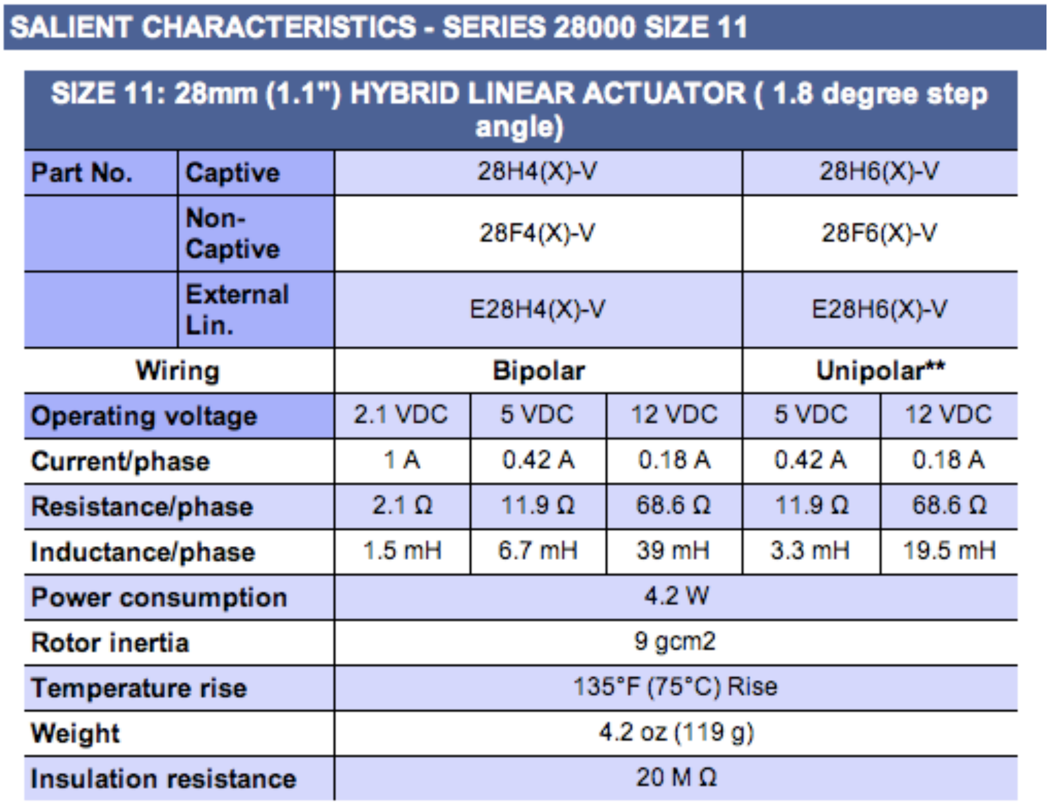


Figure 5. Power curves showing the performance of the 28000 series size 11 stepper motors [3].

Based on the above plot if we want to move a camera, which weighs about 10 lbs at a speed of 0.4 in./sec. we will opt for motor 9. This motor provides a resolution of 0.0025 in./step (0.0063mm/step). For our application we select the 28000 series, Non-captive, size 11 stepper motor with a 4 inch lead screw. The characteristics for this motor are provided in the Table 2 [5].



SALIENT CHARACTERISTICS - SERIES 28000 SIZE 11

SIZE 11: 28mm (1.1") HYBRID LINEAR ACTUATOR (1.8 degree step angle)						
Part No.	Captive	28H4(X)-V			28H6(X)-V	
	Non-Captive	28F4(X)-V			28F6(X)-V	
	External Lin.	E28H4(X)-V			E28H6(X)-V	
Wiring		Bipolar			Unipolar**	
Operating voltage		2.1 VDC	5 VDC	12 VDC	5 VDC	12 VDC
Current/phase		1 A	0.42 A	0.18 A	0.42 A	0.18 A
Resistance/phase		2.1 Ω	11.9 Ω	68.6 Ω	11.9 Ω	68.6 Ω
Inductance/phase		1.5 mH	6.7 mH	39 mH	3.3 mH	19.5 mH
Power consumption		4.2 W				
Rotor inertia		9 gcm2				
Temperature rise		135°F (75°C) Rise				
Weight		4.2 oz (119 g)				
Insulation resistance		20 M Ω				

Table 2. Salient characteristics for a Series 28000, size 11 motor [5].

To power the stepper motor we used the EZHR17ENSK starter kit, which can be purchased from All Motion [6]. The kit includes an EZHR17EN (2 Amp, 40 V) stepper motor controller plus driver, and RS485 converter and cables. We purchased the Instek PST-3201 power supply from Tequipment. This is a fairly fancy and hence expensive power supply. A cheaper more basic power supply can easily be substituted. Follow the instructions below and look at the hookup diagram shown in Figure 6 to power the stepper motor:

1. Start with power supply OFF. Connect power supply to RS485 converter.
2. Turn power on, confirm current is. Turn power off.
3. Connect EZ stepper to RS485 Converter.
4. Connect stepper motor to middle four pins of the motor connector as shown in the diagram below. Motor should execute a factory stored command.
5. If address switch is not already at 1, set it to 1 with Phillips screwdriver.
6. Turn power ON.
7. Connect RS485 converter to computer.
8. Launch a terminal window on your Linux machine and type the following command. > echo “/1A100000R” > /dev/ttySO. This will move the stepper motor to an absolute position 100000. Similarly there are other commands in the EZ stepper manual that show you how to zero the location etc.

9. Send commands to drive the lead screw to its maximum length so that only one thread is visible from the back end of the motor. Measure the length of the leadscrew emerging from the stepper motor. Note how many steps it took to get to this position and use this information to calibrate the stepper motor.

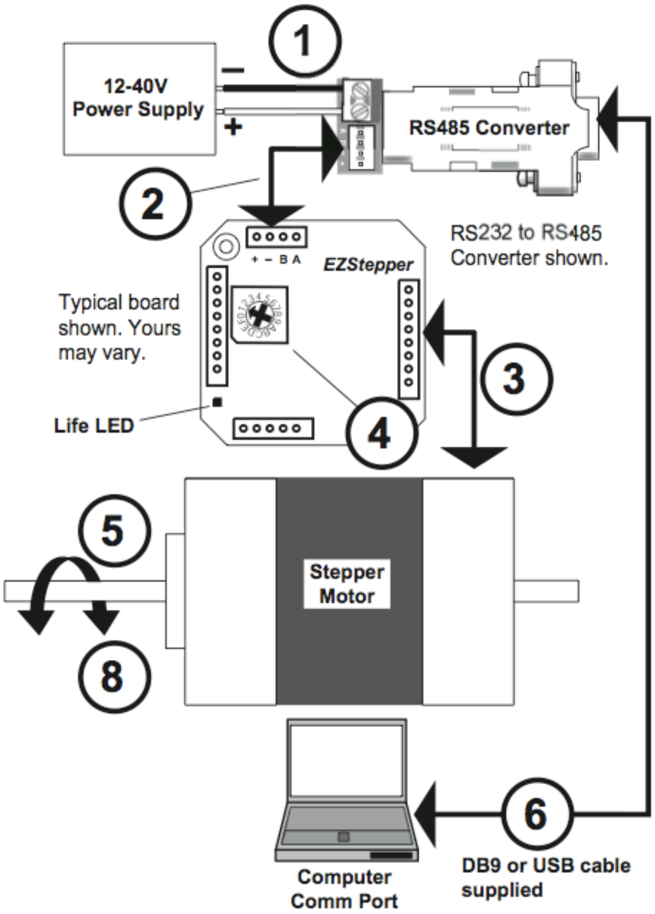


Figure 6. Schematic showing how to connect the EZ Stepper to the RS485 converter, the power supply and the computer.

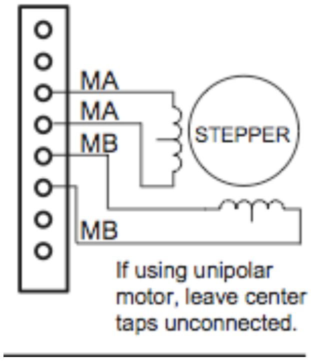


Figure 7. diagram illustrating how to connect stepper motor to motor connector [6].

We opt for ball bearing rails that can be purchased from McMaster-Carr (Figure 8) [7].

Figure 8. Telescopic Ball bearings [7].

We choose a 20 x 100 x 200 mm Aluminum plate to serve as the base of the linear translation stage. The rails are mounted on the Aluminum plate (Figure 9) and the linear stage is locked to the optical bench using 3 inch posts with ¼-20 tapped holes at the bottom and ¼-20 studs at the top (see Figure 10).

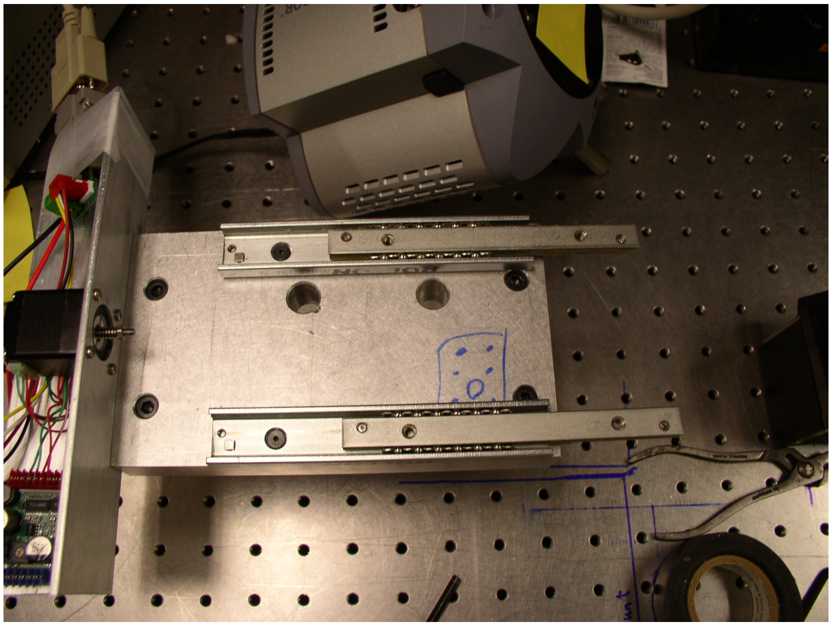


Figure 9. Ball bearing slides screwed onto the base of the translation stage. You can also see the stepper motor bolted to the 90° corner plate. The linear actuator or lead screw can be seen emerging from the hole cut out in the plate.

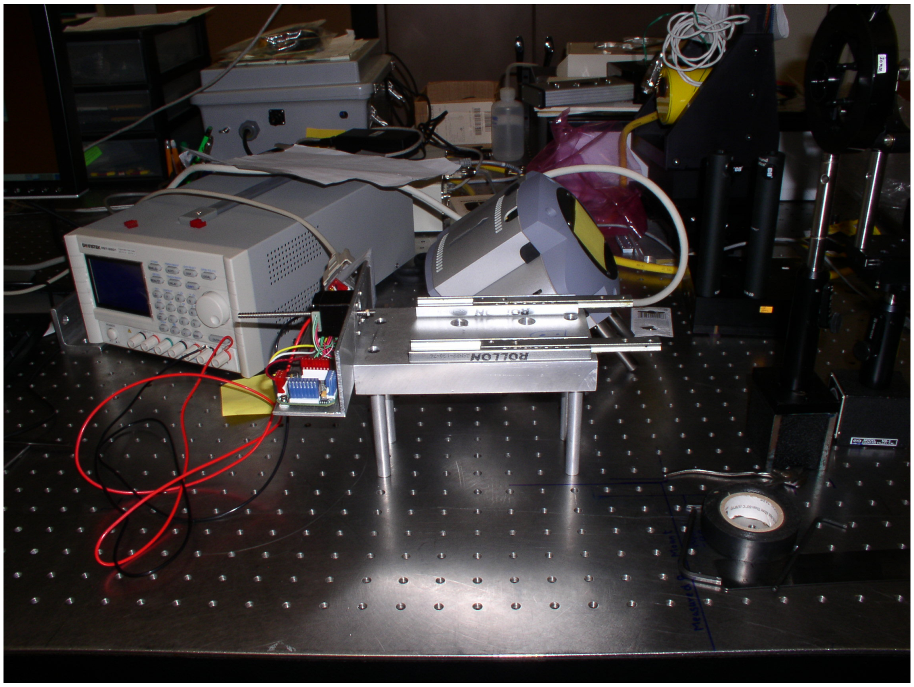


Figure 10. Translation stage locked to the optics bench with four 3 in posts.

The stepper motor along with the lead screw, the RS485 converter, and the EZ Stepper are mounted onto a 90° corner plate made of Aluminum (Figure 11). The corner plate is bolted to the translation stage and moves with it. The stepper motor is bolted onto the corner plate in which a hole is cut out from which the leadscrew emerges and drives the translation stage (Figure 9). The EZ stepper and the RS485 converter are held onto the plate with tape. The camera is mounted onto the top plate of the translation stage by screwing two 3 inch posts onto the ball bearing slides that are in turn screwed to the base of the translation stage. The final assembly for the motorized linear translation stage is shown in Figure 12.

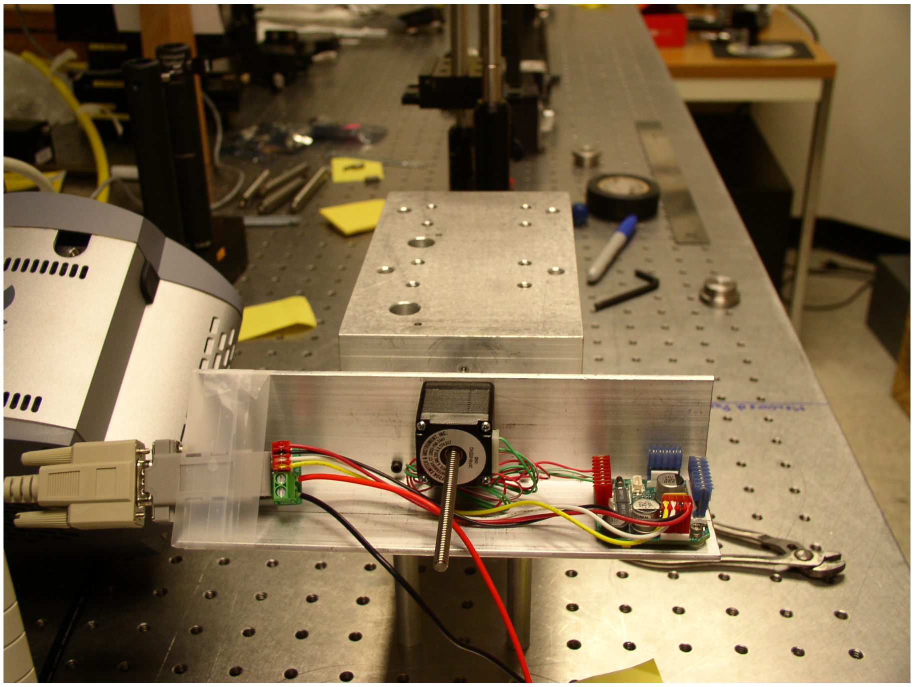


Figure 11. From right to left RS485 Converter, stepper motor with leadscrew, and EZ Stepper mounted on to the 90° corner plate.

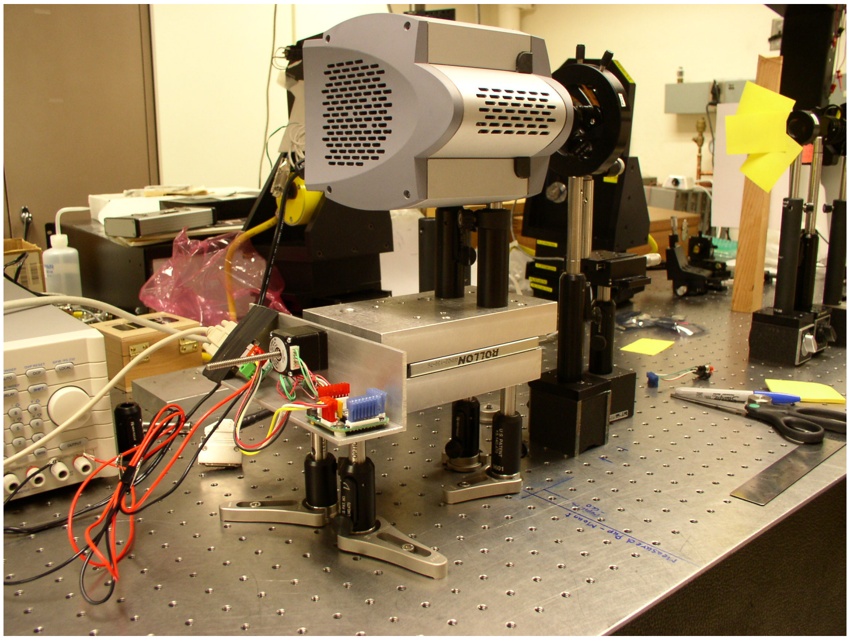


Figure 12. Fully assembled motorized linear translation stage with the camera mounted. The base of the translation stage sits on 4 posts and is locked to the optics bench. The 90° corner plate is mounted to the base of the translation stage and is thus also locked to the optics bench. The top of the translation stage is screwed to two ball bearing slides and translates as the linear actuator is driven by the stepper motor. The camera is bolted to the top plate of the translation stage with two posts. The camera translates with the top plate.

Conclusion

In this tutorial we have shown a cost effective way to build a motorized linear translation stage. A ready made translation stage without the power supply costs between $1500 to $2000 from a vendor such as Thorlabs. Whereas constructing your own motorized translation stage will cost you only $500 to $600 depending on whether you can salvage metal plates, screws and nuts from the lab and have them machined to need from the machine shop or whether you need to purchase them.

The tutorial explains how to select slides based on the precision requirements of your experiment. It also walks you through how a stepper motor produces a rotation and how that rotation translates to linear motion. The tutorial guides you in selecting the right power and resolution for the stepper motor and shows you how to power and control the stepper motor using the EZ Stepper starter kit.

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