This week, I worked on selecting the electrical components of the robot arm based on quantitative use case requirements.

Z-axis:
Use Case Requirements: 10mm/s speed, 2mm translational resolution.

We determined that the best way to achieve Z-axis motion would be a lead screw. This way, we have a large mechanical advantage, so that the weight of the gripping mechanism can be overcome without using a very powerful motor.

Fig. 1: stepper-lead screw mechanism for linear movement [1]

The vertical loading of the Z-mechanism is estimated to be 750g. This includes 300g of payload and 450g of the Z-platform itself, including the wrist rotation motor

The lead screw most commonly sold online for our dimensions (0.25m vertical motion) are T8 threads. This means for one turn of the screw, the Z-platform travels 8mm. The formula for torque to move a load is given by T = FL/(2ME), where F is the vertical load, L is the lead, E is efficiency of the lead screw and M is the coefficient of friction for the thread interface [2].

The typical lead screw has a coefficient of friction between 0.2 and 0.3, and efficiency under 0.7 [2]. Taking the middle of the typical range yields E = 0.35 and M = 0.25. F = 0.75kg * g = 7.5N. L = 8mm = 0.0008 m. Using these numbers, the required torque comes to 0.034 Nm, or 34 Ncm.

Based on the required torque, the StepperOnline 17HE24-2104S is a good selection with more than 60 Ncm of torque at 0 RPM [3].

The 17HE24-2104S has a step angle of 1.8 degrees. This is 1/200th of a rotation. We know that 1 rotation is 8mm so one step = 8mm/200. This is far better than the required translational resolution.

In order to achieve the 10mm/s speed, the motor must turn faster than (10mm/8mm = 1.25) rotations per second. 1.25 RPS = 75 RPM. Referencing the torque curve of the 17HE24-2104S, 75 RPM is near the torque peak at about 80 Ncm [3]. Therefore, the motor can easily handle the vertical load at the required speed.

With speed, resolution and torque requirements satisfied, the 17HE24-2104S is a suitable motor for the Z-axis mechanism.

XY-axis:
Use Case Requirements: 100mm/s speed, 2mm translational resolution.

For the X/Y-axis, we opted for a belt driven linear slide due to their low cost and the fact that belt mechanisms are zero-backlash.

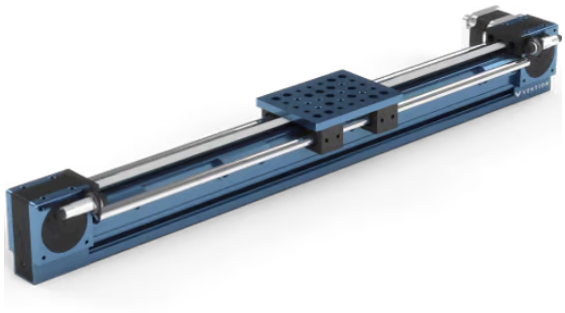

Fig. 2: stepper motor driven linear slide [4]

Unlike the Z-axis, the motor is not constantly fighting against gravity. Instead, the main constraint in the design is acceleration. While acceleration is not specified in the initial use-case requirements, we felt that 0.1m/s^2 would be a reasonable figure based on hand movement speeds when we attempt to perform daily tasks.

We have chosen to use GT2 timing belts with 20 tooth pulleys to transmit linear motion to the robot arm assembly. 20 tooth GT2 pulleys have a pitch diameter of 12.73mm [5]. This means when the belt is wrapped around the pulley, measuring from the middle of the belt's thickness, the diameter is 12.73mm.

The axis with the most moving mass will be the x-axis, since the Y/Z mechanisms are all installed on top of the x-platform in our design. A back-of envelope combined weight was set at 1.5kg. Since the mechanism slides on ball bearings, it should be sufficient to ignore friction. This puts the required translational force at 1.5kg * g = 15N. At a radius of (12.73/2) = 6.365mm, the torque required at the motor shaft is 15 * 0.00064 = 0.0096 Nm or 96mNm.

Typical stepper motors rotate 1.8 degrees, or 1/200th of a rotation per step. At 12.73mm, one rotation is approximately 40mm translational movement. Therefore, one step is 40mm/200 = 0.2mm translational motion, which is exactly our required precision.

To achieve a speed of 100mm/s, the motor needs to turn (100mm/40mm) = 2.5 times per second. This is equivalent to 150 rpm.

Based on these requirements, I chose the StepperOnline 17HE15-1504S motor. At the required speed of 150rpm, it can output 320mNm of torque, more than enough for the acceleration requirements [6] . While the torque figure can be overkill, the 17HE15-1504S is less than 1$ more expensive than smaller motors. Therefore, we feel that the commonality achieved by buying a motor with the same NEMA 17 form factor as the Z-axis motor is worth the small increase in price. We can now design one set of mounting hardware for all three axes.

Wrist Tilt Motor:
We felt that the best way to implement the wrist would be to attach the gripper directly to the shaft of the wrist tilt motor without using gears or pulleys.

In order to determine the torque required, we modeled a worst-case load scenario. This would be a long-necked flask filled with liquid.

Fig.3: worst case scenario

We are going to model this flask as a 300g mass attached to a 100mm long massless rod. This would roughly correspond to the gripper grabbing the flask by the neck. This is 300g * g * 0.1 = 0.3Nm of torque. The stepper motor selected for the X/Y axis happens to be able to achieve this torque for speeds below 540 rpm [6]. In reality, we would probably be rotating the wrist at less than a quarter of that speed. Therefore, I chose the same motor out of commonality considerations.

Power Supply:
The sum of the rated currents of the above motors comes to (1.5A/phase) * 2 phases * 3 + (2A/phase) * 2 phases * 1 = 13A. In reality, the system is very unlikely to need to reach the rated current for any sustained amount of time because the XY/wrist motors are all oversized. Stepper motors are current-controlled devices; we can limit the current by adjusting the settings of the stepper driver boards. Therefore, we have opted to use a 24V 15A power supply, just above the combined rated current, accounting for the small amount of thermal losses at the motor driver boards. The stepper motor torque curves were measured at 24V, so we chose 24V to get the same performance as advertised.

Stepper Driver
I have chosen to use 4x TB6600 stepper driver boards to control the 4 stepper motors. These boards come with a max current setting switch, should we choose to limit the current below the rated amount. They are also rated for 4A current, the same as the maximum current of the Z-axis motor. They also support microstepping, a technology that increases the quantization levels of stepper PWM signals to increase smoothness and resolution. Furthermore, they come with a metal casing, which increases the reliability of the system by improving the heat dissipation.

Arm BOM

	Count	Unit Cost ($)	Total Cost ($)	Store Link
ESP-WROOM-32 pack of 3	1	15.99	15.99	https://www.amazon.com/ESP-WROOM-32-Development-Microcontroller-Integrated-Compatible/dp/B08D5ZD528/ref=sr_1_3?dib=eyJ2IjoiMSJ9.C2zjybnvjkLUB8ybNqfUPXiLxQLQH_6HywcGtieBNQOnZQUghtyopO0WMoiBMrHb6EcmV5-18euON0ZVZmVqjqhMw6ZyjY16g37KS4a341kxfz3vkpwkYWkY6p0kYTBO6HW4TGDZIdtBWrSTdhKHKG-WpDZZjdOhdayes-47XZBrBxSTNOvSm4zva0x1RuketcAZ772AZu0_59OJTBCjLufc3vRWAljRZuJIek6akKs.EA1l8ZXMClSWrJdqSEExPObcW8ZtgD905qVXsGErTvE&dib_tag=se&keywords=ESP32

				&qid=1726841614&sr=8-3&th=1
2020v extrusion, 1500mm	1	15.99	15.99	https://openbuildspartstore.com/v-slot-20x20-linear-rail/?srsltid=AfmBOopW8FiN4PyLVIfQTm1_bu7q8YYE7wkeqlq_jsdS7PKxnjmzhjtZ
linear slides pack of 4	1	26.97	26.97	https://www.amazon.com/QWORK-V-Wheel-Aluminum-Profile-Printer/dp/B0CHYS3G96/ref=sr_1_1_sspa?crid=17RN3FR5JDTWX&dib=eyJ2IjoiMSJ9.vI_DTZoEpJ-hBYnw2EefouwitlVUaI52mbJKSZa0DDJBbcGVSlBXmzAqHoZ8RF78Yd4YfbJE5YuPvWFm1Zj1hXBtZLYeQl51BSIaZa8QAUCpGAiWia0sYtBk8w2H9kRqTrZuz0zWWY98fo8z1zpnLfIPpQnwacNaifb8MLKiEe9GXgBWdxPOhwxJFtfggzPMsvsBA8eQSN45ofTgHZJy116na6um2bwawqDyCV92jfo.DxEIkBEMu0JSr6YfBldYGzxtbxlWqn_s5NOOBQaZnvo&dib_tag=se&keywords=2020%2Bv%2Bslot%2Bslide&qid=1726951643&sprefix=2020%2Bv%2Bslot%2Bslide%2Caps%2C87&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&th=1
lead screw kit	1	12.99	12.99	https://www.amazon.com/BIQU-Copper-Coupler-Bearing-Printer/dp/B01H1QNSAE/ref=sr_1_9?crid=1VVSS3HPK6J0E&dib=eyJ2IjoiMSJ9.zZ2CZP2iSbiVjKoB4jRmYSbtEX6JfWimgp5Yi0LRgyxA89vYplwehbdSu68wUgqnEqzKXO4qKQNB05ISbGJsoGaEdB4f3MKlymMWjdbZ7w3ZGxoqlewAmPaj1LINpuylVZIrRws1M8gL0Zw-AZyXA6ljMC1Na-JvzQPTTPn6kcwQqjTnC-3O7HTRF8o1q4iyNmfnd-Bscf7QHSolLmVLZsj5ABxxFVGQKkm66Lb9qFE.FLCYCbr0Lb5DJyr7pNQpd64b_LI2ZdZoj9zQFwbPCSA&dib_tag=se&keywords=lead%2Bscrew%2B250mm%2Bkit&qid=1726952184&sprefix=lead%2Bscrew%2B250mm%2Bkit%2Caps%2C68&sr=8-9&th=1
2020 extrustion corner bracket	1	13.99	13.99	https://www.amazon.com/Aluminum-Extrusion-Connector-Brackets-Accessories/dp/B0D54C65QJ/ref=sr_1_1_sspa?crid=1MMLK4W571ABZ&dib=eyJ2IjoiMSJ9.yZ_4ugI5ZuGTj1r9LeFM1_1bME

				m9NpYDs7vd5KRvfMVtkqMX_QA2F_0VGmLmCG69yNcksh6VG0j_cMD6-uUmnCY3nmierlZArXmotTPfnevFeLEr2BRxUeQEnAKf2smn8cFg8OYPEhI505lAYr2hRiX2B93HYOoU0hk_Juy4UKKakXXAzlTAdNgpM7wnXdJcQzSjJuaM4zjnkAyb3eJixc_exzjRItbOnA5dAUwe4u8.IF12XcaGUk29SG91sS2dhK6C9atF3ScjenQVRwwuOTI&dib_tag=se&keywords=2020%2Bextrusion%2Bhardware&qid=1726953142&sprefix=2020%2Bextrusion%2Bhardware%2Caps%2C93&sr=8-1-spons&sp_csd=d2lkZ2V0TmFtZT1zcF9hdGY&th=1
2020 extrusion t slot screw/nuts	1	12.99	12.99	https://www.amazon.com/Rrina-Assortment-European-Standard-Aluminum/dp/B0BZP8T639/ref=sr_1_4?crid=2PTTSJ047CVVS&dib=eyJ2IjoiMSJ9.fPSFTeWENZMG2sln8qRAcVSNzRwEb220M0gSd3qsCFOD8Eg-3XfkIYijvCKPownZW2zPgyrfqQaYuq4CQB7Id0CxOFb4Zy4wkJy7kZNTiIqBdqwkzKbq6HoP-KW5jH0xG4iXEaUmqZZ2m7soRoSOr-sybxuXobNkx3-hvK9uJ1EvIbTKpijk0_3z-5h7j9LPGL3HVoHj82txLYJyfS3ncwRqj8WFB3bb2ASSIzKSnTY.SKjJh6yiKW_u48a7gLeR7ShIKnuvTtYNkZGnjpWnQow&dib_tag=se&keywords=2020%2Bextrusion%2Btslot%2Bnut&qid=1726953572&sprefix=2020%2Bextrusion%2Btslot%2Bnut%2Caps%2C51&sr=8-4&th=1
GT2 timing belt kit	1	9.99	9.99	https://www.amazon.com/Esakoya-Timing-Tensioner-Torsion-Printer/dp/B0CK21WWGV/ref=sr_1_6?crid=3QSS0KYGMT64C&dib=eyJ2IjoiMSJ9.k4fBNlmr-IThTnJo8IaTA1z0iqjzo6j9pcVO1TbMDH3N4AMbRaV2mlQtV6KsN6IoIx8VyFqd2iLqCpNATvoQ5gWdSMFcTGufyIY-1g3dyfWukh45SHao7yPJpmPwHh_9CBTdE_4ocj5kGq3QpNBEmLhdSOUQLZo8VwTpxUdzTDKGLnDcl3_trptJgvVc2TqPUUASzrJgROG5YewDVcggunsRTW2C382jLvNdM5rm3lw.wuyX4o7NsdFjqakk2aC_n7h4WwAnKgX_Uz__NUNRWE8&dib_tag=se&keywords=gt5+belt&qid=1726953657&sprefix=gt5+belt%2Caps%2C82&sr=8-6

Stepper controller pack of 4	1	28.99	28.99	https://www.amazon.com/TB6600-Stepper-Driver-Controller-tb6600/dp/B07RRB6BGQ/ref=sr_1_7?crid=2RPU3K83V3FLC&dib=eyJ2IjoiMSJ9.Uv3h1bGl8f4MFF8dTUPhxTgwv9TjJUbH0TqOp2f2SbejjdN_wUQJGBdeqlWkdv-MT1m8I26xxtbQUElUtebGIFGmXA5M2c9DHvd9Q58caGrkv4yR1uXE-BJw3w5sqkdJwcpT-lYMSkCK7m-jnul9KyTDKcG-b2gYdhL8tHpOU0Pg8dYIe_ieC_KnpSbKmL7DyfePoqhE4nkn-Od4Dj9GpIbgJ3lcgvnxyYLntC6uSbG7ClzFEruHCmFPb1FWpEVIDBvty2JwozG2AAZWStgiyuzXW57wxWqnz4OIqdYC0zc.GRSQEqtHQiOB5Tv-7E879CeRc4aFOcUvwez_M9si3TY&dib_tag=se&keywords=cnc+driver&qid=1727559832&sprefix=cnc+driver%2Caps%2C100&sr=8-7
NEMA 17 motor	3	6.36	19.08	https://www.omc-stepperonline.com/e-series-nema-17-bipolar-55ncm-77-88oz-in-2a-42x48mm-4-wires-w-1m-cable-connector-17he19-2004s
24V 15A power supply	1	20.98	20.98	https://www.amazon.com/AVAWO-Switching-Transformer-Regulated-Computer/dp/B0146IAXYO/ref=sr_1_4?crid=36VL2WMRNG7HL&dib=eyJ2IjoiMSJ9.F730h_oVLE8Z91EBd8eju_hriUMdji7F2r7BfNzQW6raW30cX8GTZmV7j86Q6DBzVGsJbDUTZmcaMqnR5g1zKs3f8B_PCDT9PBSqPaLDlQInrrrCL_E3TNDy2OuqU7pHQHeYiwhqRELXebQFBTb6PzB8iOJlkKQjdbbqXXDsWWo8N97HiFoOgVW4aqFGZ7SYLEEVq9-TBR9JHlXSvaKkqhmXU6YxEg4AHpAGDRkaScs.49YpdqgePlitBiT8Ewe-TJWMnjLZ92RhvB5CSx_QWSA&dib_tag=se&keywords=24v+15a+power+supply&qid=1727578922&sprefix=24v+15A%2Caps%2C111&sr=8-4
Z-axis motor	1	8.97	8.97	https://www.omc-stepperonline.com/e-series-nema-17-stepper-motor-1-8deg-60ncm-84-97oz-in-2-1a-42x42x60mm-4-wires-17he24-2104s
limit switch pack of 12	1	4.94	4.94	https://www.amazon.com/MXRS-Hinge-Momentary-Button-Switch/dp/B07MW2RPJY/ref=sr_1_4?crid=15PQS2ESK0

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[2] https://www.omc-stepperonline.com/e-series-nema-17-stepper-motor-1-8deg-60ncm-84-97oz-in-2-1a-42x42x60mm-4-wires-17he24-2104s

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[6] https://www.omc-stepperonline.com/3-pcs-e-series-nema-17-bipolar-42ncm-59-49oz-in-1-5a-42x42x38mm-4-wires-w-1m-cable-connector-3-17he15-1504s