ACS231 Group 27
Tategaki-A11 [縦書き・A11]

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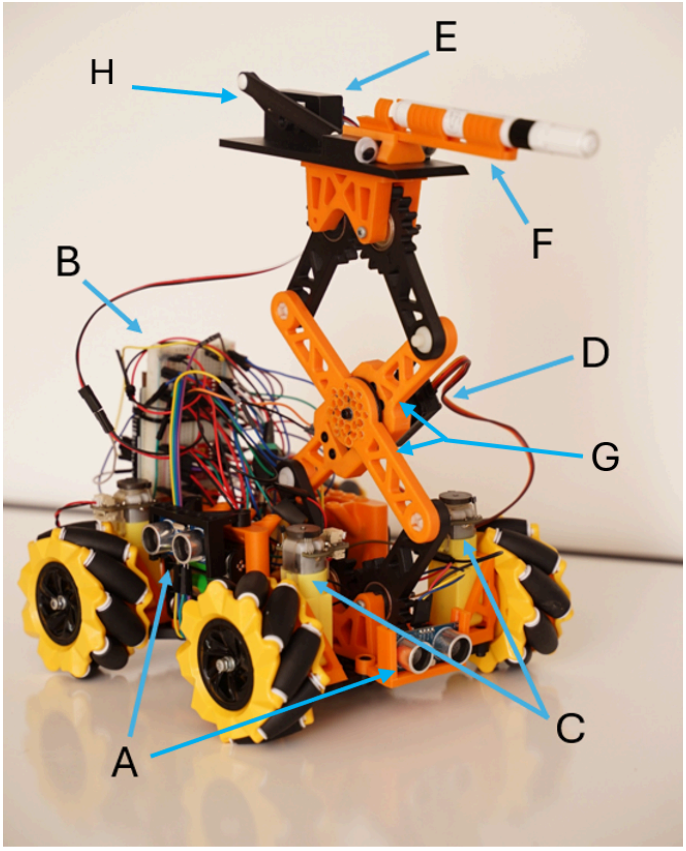
1 COMPONENT LIST & PURCHASED ITEMS
Appendix A

2 OUTSOURCED DESIGN/LIBRARY/SOFTWARE
No outsourced materials were used.

3 MECHANICAL DESIGN AND FABRICATION
The Tategaki-A11 is an autonomous mecanum wheeled mobile manipulation robot with a scissor lift and crank-release system for marker-pen operation.



$Fig.\ 1\ Tategaki - A11$
A: Ultrasonic Sensors, **B:** Breadboard, Arduino and Motor Drivers **C:** DC Motors, **D:** Arm Servo, **E:** Crank Servo, **F:** Pen Mount, **G** Scissor Lift, **H** Crank Release

Chassis Design
The chassis is a 3D-printed component designed for structural rigidity, modularity and a low-profile configuration to maintain a stable centre of gravity during scissor-lift actuation. Its reconfigurable, lightweight skeletal structure allows individual components, such as motors and sensors, to be attached using 3D-printed mounts. A structured array of conical (tapered) alignment points with captive M3 heat-set inserts enables structural reinforcement and the relocation of component mounts without redesigning the chassis.

Mount Design
3D-printed battery holder mounts are positioned laterally for easy access, while the rear section is equipped with a 3D-printed mounting bracket for the microcontroller and breadboard. 3D-printed sensor mounts are attached to the front and right sides of the robot. Mounting these components vertically on the chassis optimises their individual footprint for the compactness of the robot while keeping them accessible for adjustments and troubleshooting.

Scissor Lift Design
The 1 DOF scissor lift consists of a central X-configured mechanical arm pair actuated by a TowerPro MG996R motor for vertical displacement. It integrates with the chassis design's compact build footprint. Four 608 bearings are fitted into synchronised gears to enhance the stability and precision of the scissor lift by constraining lateral movement. At the same time, eccentric axles allow fine mesh adjustment to minimise backlash. The lift applies inverse kinematics for controlled actuation. The central X-shaped arms are reinforced to form a triangular load path, distributing stresses more efficiently. Anglepoise joints are used with tapered pivots and adjustable expansion rivets to eliminate the need for the lift's servo to continuously hold the load, improving energy efficiency and limiting wear on the motor. Upper arms extend from the top pivot points to support the lift's platform, while lower arms connect the bottom pivot points to the base, ensuring structural integrity and controlled motion.

The lift's TowerPro MG996R servo motor has a stall torque rating of 9.4-11 kg·cm; the arm attached is approximately 13.9cm; therefore,

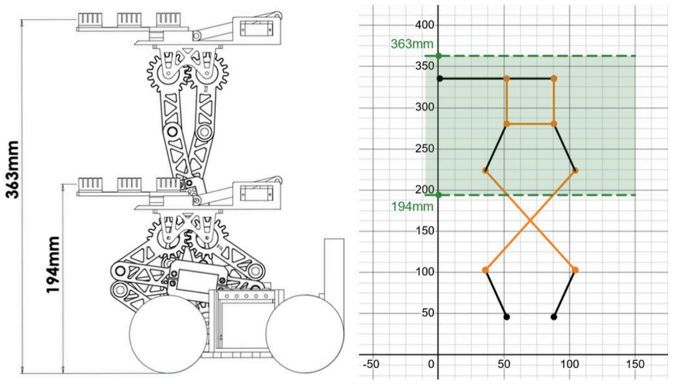
$$eq.\ 1\ Scissor\ \ Lift\ Load\ Maximum$$
$$F = \frac{\tau}{r} \Rightarrow F = \frac{9.4}{6.95} \approx 1.35kg$$

However, since the required force varies with the arm's angle, the 1.35 kg value applies only when fully extended while resisting a load. When collapsed, the force output is significantly lower:

$$eq.\ 2\ Scissor\ Lift\ work\ ratio$$

$$F_{ver} = F \cdot sin(\theta) \Rightarrow sin(25°) \approx 0.423$$

At 25° (collapsed angle), the TowerPro MG996R performs at approximately 42.3% of its ideal values (0.571 kg).

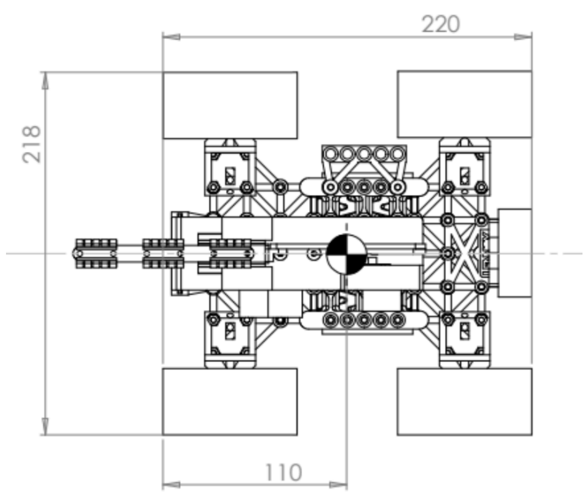


$Fig.\ 2.\ Workspace\ envelope\ of\ the\ scissor\ lift$

The robot's COG is primarily affected by the vertical movement along Z_{COG}. Minimal shifts in X_{COG} and Y_{COG} may also occur due to the lateral expansion and contraction of the scissor arms but were negligible compared to the dominant effect on Z_{COG}.

$$eq.\ 3\ Centre\ of\ Gravity\ (COG)$$

$$\frac{\Sigma(m_i \cdot z_i)}{\Sigma m_i} = Z_{COG}$$



$Fig.\ 3.\ COG\ of\ the\ robot$

Compared to 3 DOF robotic arms, which require complex inverse kinematics to maintain a straight trajectory, the scissor lift reliably achieves precise vertical motion.

Crank-Release Design

A crank-release mechanism secures the marker in a marker pen sleeve, with the marker sleeve mounted on a guided slider. A guide rail module retains the guided slider until release. A DMS-MG90 servo motor actuates the crank handle, driving a linked arm and engagement pin forward. With this, the crank release applies a controlled force to eject the slider with the mounted pen holder out of the guide rail, causing the marker pen sleeve to drop.

Fabrication Process

FDM (Fused Deposition Modelling) 3D Printing with PLA+ filament is used to fabricate all non-standard mechanical components. PLA+ contains additives that enhance toughness, impact resistance, strength, and heat resistance while allowing higher- speed printing [1]. PLA+ offers biodegradability, low energy consumption and recyclability of failed prints [1]. The 3D Printing process prioritised an optimal strength-to-weight ratio while minimising material waste through efficient print orientation and infill density selection.

A high-speed printing profile was developed to optimise production efficiency, constrained by the filament's maximum reliable volumetric flow rate. The flow rate on the printer used for this project was measured at 40 mm²/s at 135°C, with a hard velocity cap of 600 mm²/s. This optimisation significantly reduces print times compared to standard PLA+ profiles. The applied production profile specifies a 235°C nozzle temperature, a 55°C heated bed, a 160 µm layer height, three perimeter walls, four solid top and bottom layers, and 25% grid infill. For initial prototyping, a modified profile further increased speed with a 250°C nozzle temperature, a 250 µm layer height, two walls, three solid top and bottom layers, and adaptive cubic infill at twice the nozzle thickness.

Development Cycle

The robot was developed over 8 weeks, structured into four 2-week iteration cycles. Each cycle followed a systematic process to build and integrate mechanical and electronic subsystems. The Concept and Design phase, averaging 3 days per cycle, involved initial hand sketches, CAD modelling, and cardboard prototyping to validate design feasibility.

The Fabrication phase, averaging 4 days per cycle, focused on the 3D printing of non-standard components, post-processing and refinement, and preliminary fit assessments. The Assembly and Integration phase, averaging 1 day per cycle, involved mechanical assembly, electrical wiring, and final fit checks to meet design specifications. The Testing phase, averaging 2 days per cycle, included functional testing, failure analysis, and iterative modifications.

4 ELECTRONICS

The robot's electrical system was designed to efficiently manage sensor input, motion control, and actuation while ensuring reliable power distribution.

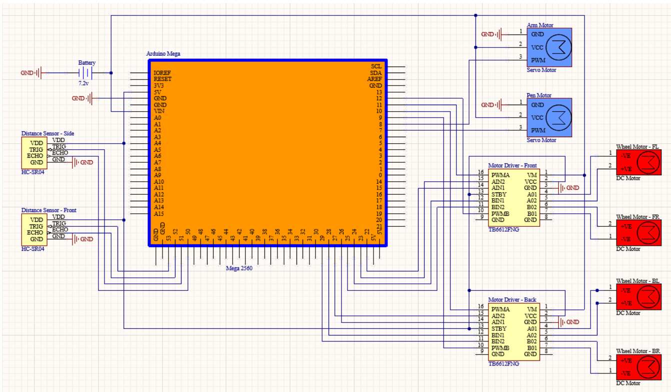


Fig. 4 Schematic of the electronic circuit

Microcontroller

An Arduino Mega 2560 controls sensor input, motion and actuation. Its expanded I/O capabilities provide 54 digital pins, including 15 that support PWM output [2]. The initially considered use of an Arduino Uno R3 was ruled out due to its limited 14 digital I/O pins and 6 analogue inputs [3], which failed to meet the system's requirements.

Sensors

Two HC-SR04 Ultrasonic Sensors provide input for navigation. Early designs included two Ultrasonic sensors in combination with DC encoders and a 6DOF IMU. However, testing confirmed that the ultrasonic sensors alone provide sufficient distance measurements for reliable obstacle detection and wall-following navigation. Their time-of-flight principle enables accurate distance estimation within 2 to 400 cm, with a resolution of approximately 3 mm [4]. Removing encoders and IMU simplifies the control system by reducing sensor fusion requirements.

Motors

Four DFRobot FIT0450 DC motors drive the mecanum wheels, enabling omnidirectional movement through differential wheel speeds. Their 120:1 gear reduction balances speed and torque, providing a no-load speed of 160 rpm at 6V [5]. While the stall torque of 0.8 kgf·cm [5] is lower than that of high-torque servos, it provides sufficient force for controlled mecanum wheel actuation. The DFRobot motors were controlled by two TB6612FNG motor drivers, allowing power and directional control using PWM pins and H bridges [6].

A TowerPro MG996R servo motor drives the vertical displacement of the scissor lift. It operates between 4.8V and 7.2V, drawing up to 2.5A at a 6V stall with a peak power consumption of around 15W [7]. The MG996R provides a stall torque of 9.4 kg·cm at 4.8V and 11 kg·cm at 6V [7], sufficient to reliably overcome the load and friction in the scissor lift mechanism.

A DMS-MG90 micro servo motor actuates the crank-release mechanism. It operates at 4.8V to 6V with a peak power consumption of approximately 1.5W and a stall current of 650 mA [8]. The crank handle requires minimal torque, well within the MG90's stall torque of 1.8 kg·cm at 4.8V [8], ensuring reliable actuation. The servo's 180°±10° rotation range aligns with the required crank motion [8].

Power Supply

The robot's power supply consists of six Nickel Metal Hydride (NiMH) cylindrical cells (1.2V nominal, 2600mAh capacity, 7800mAh high discharge rate) [9], providing stable voltage and sufficient current for all components. In comparison, testing revealed that off-the-shelf non-rechargeable 1.5V AA batteries failed to deliver the required current. The six-cell configuration ensures compatibility with the Arduino Mega 2560's recommended 7–12V [2] input range and meets the current demands of the motors. Based on power consumption calculations, the robot's average power usage is approximately 54.5W, resulting in a continuous operating time of around 20.6 minutes. This estimation assumes uninterrupted operation without idle periods. A dual power distribution system separates the Arduino power supply and sensors from the motors. This separation prevents voltage drops and current surges caused by high-power actuation components from affecting the low-power control electronics.

Circuit Assembly

The circuit is built on a breadboard. A soldered protoboard (stripboard) design was considered but deselected to allow faster iterative modifications during development. While 22 AWG jumper wires are suitable for prototyping the robot, a lower AWG wire with a higher current-carrying capacity would enhance the robot's power circuitry reliability. DuPont connectors were used throughout the system to ensure secure yet modifiable wiring.

5 CONTROL

The robot follows a structured sequence of operations controlled by a finite state machine (FSM) [10], guiding it through navigation and task execution. The control system primarily relies on ultrasonic sensors to detect distances and determine movement decisions. The FSM is implemented within the loop() function, where each step represents a distinct phase in the robot's operation.

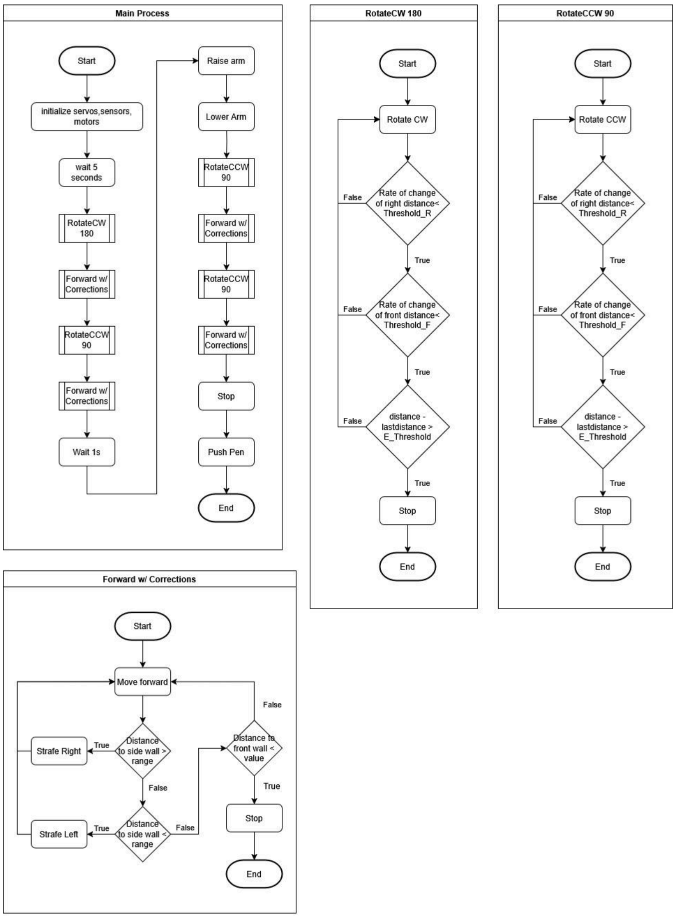


Fig. 5 Simplified operational logic/ main algorithm

Each step corresponds to a specific task, progressing sequentially as conditions are met. Initially, the robot executes a 180-degree clockwise turn, adjusting its orientation based on the rate of change of the ultrasonic sensors. Once the rate passes a manually tested negative threshold, it will stop. Once aligned, it advances while maintaining a fixed distance from the right-hand wall, using ultrasonic sensor readings to make corrective strafing adjustments. Upon detecting the front wall, the FSM transitions to a 90-degree counterclockwise turn. Once the robot reaches the whiteboard, the height of the scissor lift is adjusted using inverse kinematics to maintain precise positional values with an MG996R servo. After drawing a vertical line on the whiteboard, the robot performs a 90-degree counterclockwise turn and continues navigating the course. Upon reaching the endpoint, the pen holder is dropped with a crank release mechanism using an MG90 servo. After repeated successful runs the estimated completion time for a single course run is approximately 30 seconds.

Kinematics

The equations[eq. 4, eq. 5] describe the scissor lift's kinematics, referring to the relationship between the MG996R servo angle and the vertical displacement.

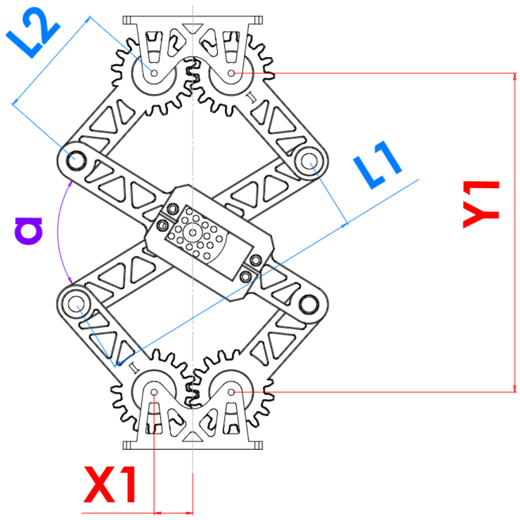


Fig. 6 Kinematics of scissor lift

eq. 4 inverse Kinematics

$$\alpha = 2\cdot\left(\frac{\pi}{2} - \arccos\left(\frac{L_2^{\,2}-\left(\frac{L_1}{2}\right)^2-\left(\sqrt{x_1^{\,2}+\left(\frac{y_1}{2}\right)^2}\right)^2}{-2\cdot\left(\frac{L_1}{2}\right)\cdot\left(\sqrt{x_1^{\,2}+\left(\frac{y_1}{2}\right)^2}\right)}\right) - \arctan\left(\frac{2\cdot x_1}{y_1}\right)\right)$$

eq. 5 Forward Kinematics.

$$y_1 = \left(\frac{L_1}{2}\right)\cdot\sin\left(\frac{\alpha}{2}\right) + L_2\sin\left(\arccos\left(\frac{\left(\frac{L_1}{2}\cdot\cos\left(\frac{\alpha}{2}\right)-x_1\right)}{L_2}\right)\right)$$

Since the scissor lift operates with only 1 DOF, its inverse kinematics are more simplistic than a higher DOF robotic arm. Higher DOF robotic arms often have several valid configurations for reaching the same Cartesian coordinate, requiring additional control strategies. However, the scissor lift follows a strictly defined singular vertical trajectory.

Appendix A

Component-Code	Descriptor	Product ID / File Name	Qty	Cost Per Unit	Costs Subtotal	Weight (g) Per Unit	Weight (g) Subtotal	Link	Labels in Figure 1
LOC									
LOC-RNG-WHE	Mecanum Wheels Set (4)	1738-FIT0653-ND	1	£15.00	£15.00	390	390	DigiKey	—
LOC-RNG-MTR	DC Motor with Encoder	DFRobot FIT0450	4	£0.00	£0.00	50	200	DFRobot	C
LOC-RNG-MSH	Motor Shaft	LOC-RNG-MSH.STEP	4	£0.02	£0.08	0.59	2.36	CAD	C
LOC-RNG-MNT	Motor Mount	LOC-RNG-MNT.STEP	4	£0.26	£1.02	8.53	34.12	CAD	C
LOC-CHA	Chassis	LOC-CHA.STEP	1	£1.53	£1.53	50.93	50.93	CAD	—
MAN									
MAN-SCL-MTR	Servo Motor	TowerPro MG996R	1	£0.00	£0.00	55	55	DigiKey	D
MAN-SCL-MA1	Motored Arm 1	MAN-SCL-MSA.STEP	1	£0.47	£0.47	15.82	15.82	CAD	G
MAN-SCL-MA2	Motored Arm 2	MAN-SCL-MA2.STEP	1	£0.36	£0.36	12.1	12.1	CAD	G
MAN-SCL-GA1	Geared Arm 1	MAN-SCL-GA1.STEP	2	£0.22	£0.44	7.35	14.7	CAD	G
MAN-SCL-GA2	Geared Arm 2	MAN-SCL-GA2.STEP	2	£0.22	£0.44	7.35	14.7	CAD	G
MAN-SCL-AXL	Axles (Geared Arm)	MAN-SCL-AXL.STEP	4	£0.01	£0.06	0.49	1.96	CAD	G
MAN-SCL-LPB	Lift Pivot Base	MAN-SCL-LPB.STEP	2	£0.38	£0.75	12.54	25.08	CAD	G
MAN-EEF-MTR	Servo Motor	DMS-MG90	1	£0.00	£0.00	13.4	13.4	DigiKey	E
MAN-EEF-SLI	Slider Insert	MAN-EEF-SLI.STEP	1	£0.14	£0.14	4.71	4.71	CAD	H
MAN-EEF-PLF	Platform	MAN-EEF-PLF.STEP	1	£0.78	£0.78	26.15	26.15	CAD	H
MAN-EEF-CRH	Crank Handle	MAN-EEF-CRH.STEP	1	£0.03	£0.03	1.04	1.04	CAD	H
MAN-EEF-CLA	Crank Linked Arm	MAN-EEF-CLA.STEP	1	£0.07	£0.07	2.37	2.37	CAD	H
MAN-EEF-EGP	Engagement Pin	MAN-EEF-EGP.STEP	1	£0.03	£0.03	1.12	1.12	CAD	H
MAN-EEF-MHS	Marker Holding Sleeve	MAN-EEF-MHS.STEP	1	£0.24	£0.24	7.99	7.99	CAD	F
MAN-EEF-MKR	Marker	NA	2	£0.10	£0.20	12	12	NA	F
SEN									
SEN-NVG-UDS	Ultrasonic Sensors	HC-SR04	2	£2.50	£5.00	9	18	Handson	A
SEN-NVG-MNT	Sensor Mount	SEN-MNT.STEP	2	£0.16	£0.31	5.17	10.34	CAD	—
CTR									
CTR-MIC	Microcontroller	Arduino Mega 2560 Rev3	1	£0.00	£0.00	37	37	Arduino	B
CTR-MIC-MNT	Microcontroller Mount	CTR-MIC-MNT.STEP	1	£0.31	£0.32	10.32	10.32	NA	—
CTR-BRB	Breadboard	Breadboard (400-point)	1	£0.00	£0.00	38	38	NA	B
CTR-MTD	Motor Driver	TB6612FNG	2	£0.00	£0.00	3	6	SparkFun	B
PWS									
PWS-BAT	Rechargeable NiMH Cells	NA	6	£2.00	£12.00	31	186	RS Online	—
PWS-BHL	Battery Cell Holder	NA	2	£2.00	£4.00	9.4	18.8	NA	—
PWS-BHL-MNT	Battery Cell Holder Mount	PWS-BHL-MNT.STEP	2	£0.71	£1.41	23.56	47.12	NA	—
MSC									
MSC-FIX	Screws, Bolts, Rivets	NA	NA	NA	NA	ignorable	ignorable	NA	—
MSC-WIR	Wires	22-AWG	NA	NA	NA	ignorable	ignorable	NA	—
			Total Costs:		**£43.29**	**Weight (g):**	**1257.13**		

Table Legend for Component-Codes:
L1 LOC (Locomotion); MAN (Manipulation); SEN (Sensors); CTR (Control); PWS (Power System); MSC (Miscellaneous); **L2** RNG (Running Gear); CHA (Chassis); SCL (Scissor Lift); EEF (End-Effector); NVG (Navigation); BRB (Breadboard); MIC (Microcontroller); BAT (Batteries); BHL (Battery Holder); FIX (Fixings); WIR (Wires); MTD (Motor Driver); **L3** WHE (Wheels); MTR (Motor); MSH (Motor Shaft); MNT (Mount); MA1 (Motored Arm 1); MA2 (Motored Arm 2); GA1 (Geared Arm 1); GA2 (Geared Arm 2); RIV (Rivets); AXL (Axles); LPB (Lift Pivot Base); SLI (Slider); PLF (Platform); CRH (Crank Handle); CLA (Crank Linked Arm); EGP (Engagement Pin); MHS (Marker Holding Sleeve); MKR (Marker); UDS (Ultrasonic Distance Sensors).

Table 1: Mechanical and electronic components and material list

Reflection on Group Project

As a group
This experience reinforced the idea that collaboration is key in projects. Our differing perspectives and approaches allow for unique solutions through consistent communication. A hurdle we had to overcome was time management. Despite this, our efficiency in delegating tasks and adjusting to the reality on the ground allowed for steady and continuous progress, ensuring no member was overwhelmed. This allowed us to focus on improving our project management and organisational skills as the project progressed.

Simon Lennox
The ACS231 Mechatronics project was an apt vessel to solidify our theoretical mechatronics knowledge gained thus far in the course. As with all group projects, interpersonal, intergroup, leadership and communication skills were thoroughly tested and came out better for it. As a group it was apparent that the main thing learnt from the project was consolidating academic theory with it’s real world connotations, as well as serving a brief introduction to a wide variety of manufacturing methods and design optimisation. Personal learning points were largely that of epistemology and strategy with respect to working in a team. My personal contribution was mechanical design drafting, prototyping & manufacture.

Dirc-Robert Wortley
The ACS231 Group Project provided an opportunity to learn how to operate a more complex project within an academic environment alongside fellow students and academic teaching staff. The herein-encountered challenges will inform the planning and organisation of similar future projects at the University of Sheffield. Due to insufficient time, the possibility of learning beyond preexisting knowledge was minimal. My contributions to the project focussed mainly on early design and ideation, some CAD Modelling in Fusion360 and technical report writing.

Will Sartin
My main tasks were to help construct the final robot design and design the wiring schematics based on the connections that were decided on during the build phase. I think as a group, we were good at designating tasks and identifying key deliverables for the project as a whole. I learned how to help identify tasks that could be completed outside of group work that could help our time spent together be more productive and valuable.

Connor Farnell
During this project, I gained more hands-on experience with the design & fabrication process. However, my main tasks were more software-based learning to work on code in collaboration with other people is an important skill that I didn’t appreciate as much until recently, iterating on algorithms and more efficiently identifying and resolving issues, being able to discuss, compromise and adapt to the way others approach a problem strengthened my soft skills and has given me further insight into collaborative design.

Jintao Yu
(Not in the country / Away)

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