# Prototype Concept Overview

## Prototype Concept Summary

This prototype demonstrates the Design Concept as an integrated control system, particularly focusing on how wind input can be fed into actuators to produce an output configuration that will maximize dust prevention. This prototype does not incorporate the responses to precipitation and sun position, as it was judged that responses to precipitation would be redundant to the purpose of the prototype, and that doing the necessary calculations to balance between sun exposure and wind blockage was beyond the scope of this prototype. Additionally, it does not simulate all the physical characteristics of the Design Concept, such as barrier shape, distance between barrier and panel, and panel material. The prototype consists of three main subsystems: a sensor subsystem that includes sensors for both wind speed and direction, a barrier subsystem that actuates a moving barrier around a track, and a panel subsystem that actuates a motor connected to a simulated solar panel shape. These subsystems are all connected to a central Arduino Uno microcontroller, and all components except for the sensors are housed in a laser-cut wooden box.

Figure 1: An image of our final prototype.

## System Architecture Diagram

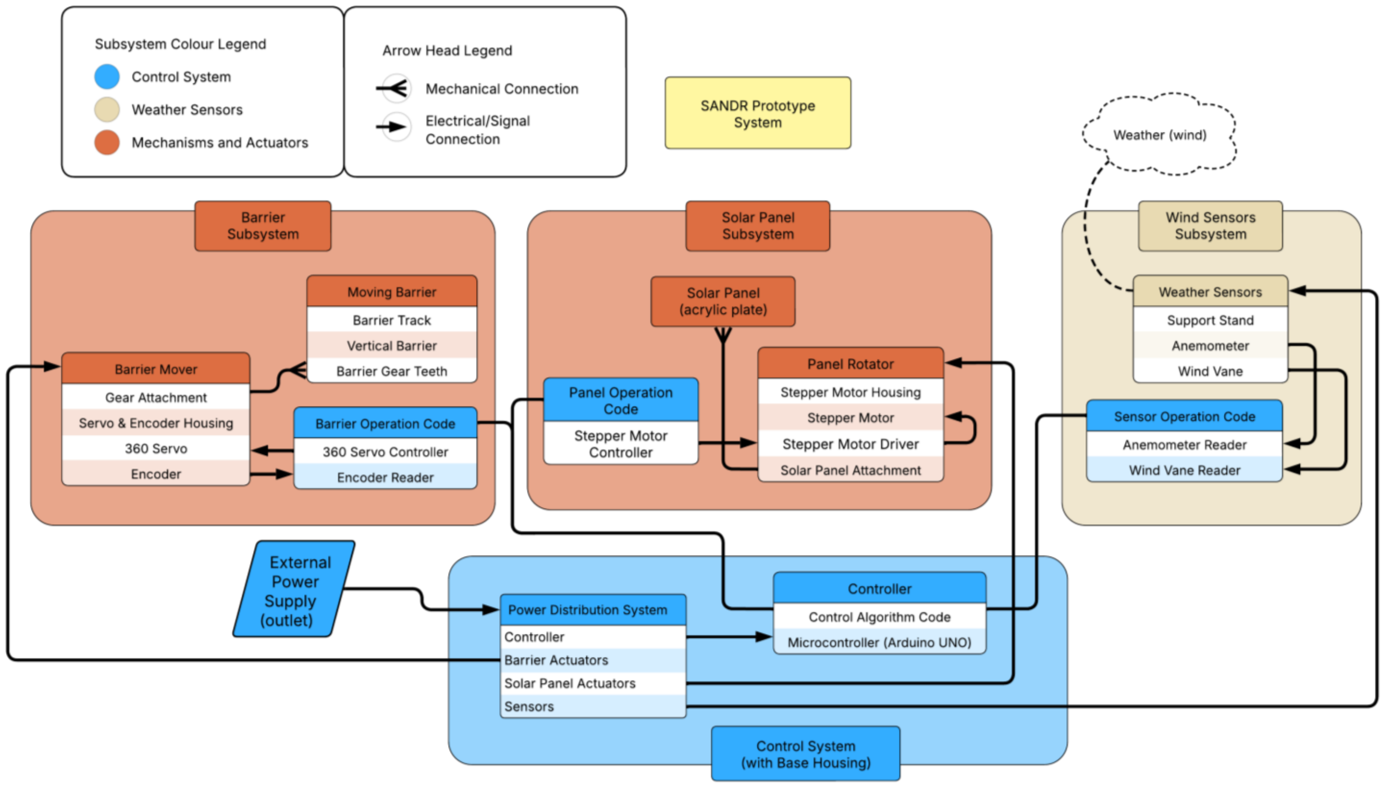


Figure 2. System architecture diagram of the prototype.

## Barrier Subsystem

### Design

The purpose of this subsystem is to provide a barrier that is capable of blocking windborne dust and that can move around the solar panel to any desired angle. One key design decision was to use a circular track instead of the rounded rectangle used in the Design Concept, since a circular track is much easier to prototype. Since the shape of the barrier is not the most unbelievable part of the design, it was justified to make this change.

Originally, the track was too deep for the barrier which meant instead of rolling on the bearings, it was just rolling on the edge of the barrier, adding friction. This was fixed by printing fillings that slotted into the track to elevate the barrier more (Figure 4). In addition, there were some issues with the sizing of the parts being too large, so it had to be reprinted. For example, the axles for the bearings were initially too large, as seen in Figure 2.

The gear underwent two iterations. The first gear that was printed was not made with the shape of the encoder or the servo motor attachment in mind so neither fit at all. (Figure 6) The next gear iteration included a depression in the shape of the servo attachment, but it required a lot of shaving down to fit as seen in Figures 5-8. The final gear that was printed was made larger and with more precise slots for the encoder and servo, so both attachments fit easily and required no shaving down.

One challenge was placing the gear structure in the right place. At first, the gear was too close to the barrier so it had to be removed and repositioned which was difficult as it was hot glued down the wooden box (Figure 14). After readjusting the gear, it turned out that the gear was slightly too far away, and the teeth would sometimes have trouble catching. This was fixed by inserting tape into the crack between the two barrier parts, as well as taping it secure. Thus, the barrier is pressed tighter against the gears, giving a better catch between the gears and barrier.

### Performance Against Specifications

The barrier meets both movement-related specifications (SP-BAR-01 – rotate 360 degrees; SP-BAR-02 – move slower than 15cm/s). It is able to rotate fully both in the clockwise and counterclockwise directions and has a speed of 8.98cm/s, slower than the 15cm/s constraint. There is a slight discontinuity in the movement of the barrier at the blue gear, as seen at 11s. This impacts the accuracy of the movement but does not prevent the barrier from successfully rotating 360 degrees. The barrier is observed to effectively block sand from accumulating on the panel in accordance with SP-BAR-03.

## Panel Subsystem

### Design

Since the solar panel plays a key role within the design, a smaller custom simulated panel was CAD-modelled and printed rather than using a full-size test rig. Originally, two 180° servo motors were planned to simulate both the orientation and the tilting of the solar panel, as seen in Figure 1. However, upon further discussion, it was decided that tilt control was not necessary to simulate the prototype's response, so it was decided to put the panel on a manually adjustable axle and rotate it around the z-axis using a stepper motor, as seen in Figures 2 and 3.

When printing the stand to store the stepper motor, a hole to plug in the power cable was not accounted for, as seen in Figure 3. Another significant challenge involved the sizing of the 3D prints. Initially, the panel and its axle were designed to fit snugly together by making the axle slightly larger than the hole, but this ended up being too tight of a fit and some of the pieces snapped, as seen in Figure 1. Additionally, one of the cylindrical axles with the hole facing downwards rather than upwards which meant it was extremely difficult to remove the supports. Both parts were eventually reprinted, with an adjusted hole size and an upward-facing hole. During the process of getting the axle to fit the panel, the components were slowly abraded by friction, and eventually the connection became too loose. As seen in Figure 4, elastic bands were used to tighten the connection again. Tape was also added inside the motor stand to make the stepper motor fit more snugly as seen here. This reduced the noise caused by the motor vibrating against its stand.

### Performance Against Specifications

The panel is able to successfully turn 360 degrees on the X-Y plane in the clockwise and counterclockwise direction. While it is observed that the tilt of the panel changes slightly while rotating which was due to a gap within the connection, it does not have any effect on the ability of the panel to rotate 360 degrees.

## Sensor Subsystem

### Design

The goal of the sensor subsystem is to continuously collect data on both wind direction and wind speed, in order to inform the behaviour of the actuators (the barrier and panel). Designs for the wind speed sensor, also known as an anemometer, included a "sail" attached to a lever arm that would push on a force sensor, a similar design attached to a button (since the sensor only needs to register a threshold rather than a continuous range of values), and a cup anemometer consisting of hollow hemispherical arms rotating around a rotary encoder (Wind_Sensor_Brainstorming). This last option was chosen because it had reference designs to back it up (Reference Designs), and there were concerns that the wind would not produce enough force to trigger the button or the weight sensor (whose intended range was 1-10kg). The obvious choice for the angle sensor was to make a vane with a large tail surface area (Reference Designs), and attach it to a rotary encoder, however, upon acquiring an encoder, it was found that it had much more resistance to torque than expected, so we started brainstorming other options (Wind_Sensor_Brainstorming). After reviewing the pros and cons of each option,  design with a vane and an ultrasonic sensor rotating on a ball bearing, surrounded by a spiral wall which would allow for distance measurements to be translated into angle readings. This was later modified to have the sensor fixed and the spiral rotating with the vane, in order to avoid wires getting tangled. Although this made the design quite bulky, rough calculations indicated that the wind would be able to turn it. After printing this design (see Vane_Arrow and Weather_Vane) and wiring it to a Pico to take measurements, it was discovered that the sound pulses from the sensor were bouncing off the curved wall at an angle, resulting in inaccurate measurements and meaning that each angle did not correspond to a unique distance measurement (Ultrasonic Wind Vane). Around this time, the anemometer was printed, and it was found that with more leverage, the encoder turned quite easily. As a result, the original plan of attaching the vane to an encoder was reinstated, and redesigned the arrow with two tails sticking out at 45 degree angles, so that there would always be a normal component to the wind force on the tail. This final version of the design can be seen in action here.

### Performance Against Specifications

The sensors were compared to the specifications using these protocols, and the results can be found here. The anemometer is able to successfully differentiate high wind from low wind (demonstration) and the wind vane is generally able to read wind angle changes accurately (demonstration). However, the quadrature encoder library used is occasionally inconsistent in its readings of angle changes (see Arduino Code V5).

## Integrated System

### Design

During integration, it was realized that due to the additional height from the stepper motor, the top of the panel was higher than the barrier. This led us to the idea of a wooden box with a hole in the middle for the panel, so that the barrier would be raised above the panel. This box had the additional benefit of covering up all the wires and electrical components of the prototype (Figures 6 and 7). As seen in Figures 1 and 2, the original laser cut of the box did not quite fit, so it was sawed and sanded down (Figure 3). The working version can be seen in Figure 4. Furthermore, it was observed during integration was that if the sensors were at ground level, it would not be able to catch the wind from all directions as it would be blocked by the barrier. To fix this, a wooden platform was nailed together to support the sensors (Figures 8, 9 and 10).

The Arduino code was the key to communicating between all the subsystems, and as such, there were many challenges with the code during integration, as seen here.

### Performance Against Specifications

The majority of the circuit is colour-coded, apart from some of the wires for the encoders where we could not acquire the correct jumper wires, meeting SP-INT-01. The prototype also meets SP-INT-02 (easy disassembly and reassembly). The lid of the prototype base can be easily lifted, allowing access to the circuit underneath and the connection wire for the Arduino Uno can be easily disconnected and reconnected.

SP-INT-03 and SP-INT-04 are also met: the barrier moves only when the wind direction has changed by more than 45 degrees (Demonstration), which in our prototype is approximated using 2 detents (~36 degrees) of the rotary encoder. The barrier also moves in response to the wind crossing the high-speed threshold (Demonstration), which is approximated using hair dryer settings in our prototype.

Like the barrier, the panel meets SP-INT-07 and SP-INT-08 as it only rotates when the wind direction has changed by more than 45 degrees (Demonstration). It also stays stationary in low wind conditions and moves when it detects high wind, meeting SP-INT-09 (Demonstration).

For SP-INT-06 and SP-INT-10 (angle deviations of the barrier and panel from the target positions), the prototype did not perform ideally, as there was a significant angle deviation for all three trials. It was also seen throughout the 3 trials that the performance of the system was inconsistent: trial 2 yielded better overall results compared to trials 1 and 3. The angle deviations also varied significantly between the panel and barrier with the panel under turning more in most of the trials. The final deviations of the panel and barrier were within the 45-degree margin of error needed for the design to function, but over a longer period of time this deviation could accumulate and significantly impact performance. While integrating the system and performing testing, the team noticed hardware limitations that contributed to this error. Firstly, the mount for the panel onto the stepper motor was slightly loose, reducing the amount of friction causing the panel to under turn. The team tried to overcome this by adding masking tape to reduce the gap, which led to an improvement but did not eliminate all slippage. Another factor that might have contributed to this error was imperfections within the barrier track and gear connections. As mentioned earlier, there was one portion in the track where the gear for the barrier was slightly too far, causing the barrier to sometimes slip (Figure 2). Finally, the previously mentioned inaccuracies with the encoder library may have led to inaccurate sensor readings and thus inaccurate target angles within the code.

## Conclusion

Upon completion, the final prototype meets nearly all the required specifications. The barrier and panel can change orientation throughout 360 degrees, the sensors can measure wind speed and direction, and the central control system can use the sensor data to produce responses in the actuators. The barrier can effectively block dust in its low-wind mode, and the design is easy to use and repair. The one area in which the prototype is lacking is the accuracy of the barrier and panel movements, due to various mechanical issues highlighted above. This is something that can be improved upon in future prototypes.

The iterative construction and testing of the prototype provided critical insights into the performance of the proposed design concept. By validating against key requirements FO-1 and FO-3.3, it was shown that the system can effectively respond to changing weather conditions in order to achieve the actuator configuration that minimizes dust accumulation The following are some key takeaways from the prototyping process:

1. **Maintaining accuracy for barrier and panel orientation:** The prototype demonstrated challenges in maintaining precise position (SP-INT-06 and SP-INT-10) -- inconsistencies were observed in positioning after repeating trials. This is critical for the effectiveness of the system's core functionality. However, the major cause of these inaccuracies was the limitation of MyFab's available sensors and encoders which restricted high-precision feedback control. Since these constraints were beyond control, it emphasized that the final design should be constructed with modularity in mind. To improve precision, alternative sensors and better calibration algorithms can be considered to increase the effectiveness of our system
2. **Importance of sand proofing our elements:** From testing, it was discovered that while the system was effective in block sand from reaching the panels as shown in SP-BAR-03, sand is present on other critical components including the track, hardware, and beneath the panel, posing potential risks. If this is left unaddressed, excess sand can lead to mechanical obstructions and degradation of moving parts. This finding emphasized more need for more protective coatings for hardware components and self-cleaning dust removal strategies in the final design concept.

For future improvements, future iterations will focus on improving accuracy, sand proofing, and energy efficiency. Higher precision motors and sensors will be explored to optimize barrier and panel positioning. Sand-resistant materials and more protective coatings will be implemented to prevent mechanical failures. Additionally, energy efficient control algorithms and hardware will be developed to ensure that the system does not consume more power than the energy gained from cleaner panels. The prototype can also be expanded to go beyond wind conditions and respond to sun, rain, and nighttime conditions, requiring more complex algorithms to be implemented. Future testing will refine how the system balances multiple environmental factors while maintaining efficiency.