

Modeling and Analysis of an Intelligent 2-DOF Spherical Parallel Steering System for Active Reflector Control in Next-Generation RadioTelescopes

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Abstract

To address the limited sky coverage and lack of flexibility in the fixed 5-meter radio telescope at Princess Nourah University, we developed a mechanical enhancement featuring a lightweight secondary mesh mirror mounted on a two-degree-of-freedom (2-DoF) arm. The system uses a stepper motor for horizontal rotation and a servo motor for elevation control, allowing the mirror to redirect incoming radio signals into a fixed feed horn with improved accuracy and reduced signal loss. This setup enables the telescope to access a wider area of the sky without repositioning the main dish or altering the primary structure. The design improves observational flexibility, enhances signal reception reliability, and lays the foundation for future upgrades involving intelligent control systems for automatic celestial tracking and dynamic alignment.

Introduction

Radio astronomy plays a vital role in understanding the structure and dynamics of our galaxy through the observation of cosmic radio emissions—most notably, the 21 cm hydrogen line at 1420 MHz. At Princess Nourah University (PNU), a 5-meter parabolic radio telescope was developed to observe this spectral line, providing valuable educational and research opportunities. However, the telescope’s fixed structure limits its field of view and its ability to track moving celestial objects, which reduces observational flexibility.

To address these limitations, our project proposes an innovative mechanical enhancement: the addition of a lightweight secondary parabolic mesh mirror mounted on a two-degree-of-freedom (2-DOF) arm. This mirror reflects incoming signals from a broader sky region into a dedicated feed horn antenna, which is aligned precisely at the mirror’s focal point.

This system allows:

- Wider sky coverage without increasing the main dish’s diameter.
- Object tracking across different angles.
- Signal amplification by redirecting additional energy into the system.

System Model

To enhance the angular coverage of the fixed radio telescope at Princess Nourah University, we designed a 2-Degree-of-Freedom (2-DoF) mirror-based tracking system. The design introduces a movable mesh parabolic mirror mounted on a parallel mechanical arm that enables full 360° azimuthal rotation and adjustable elevation elevation.This allows the mirror to reflect signals from more parts of the sky without needing to move the main dish.

The steering system consists of:

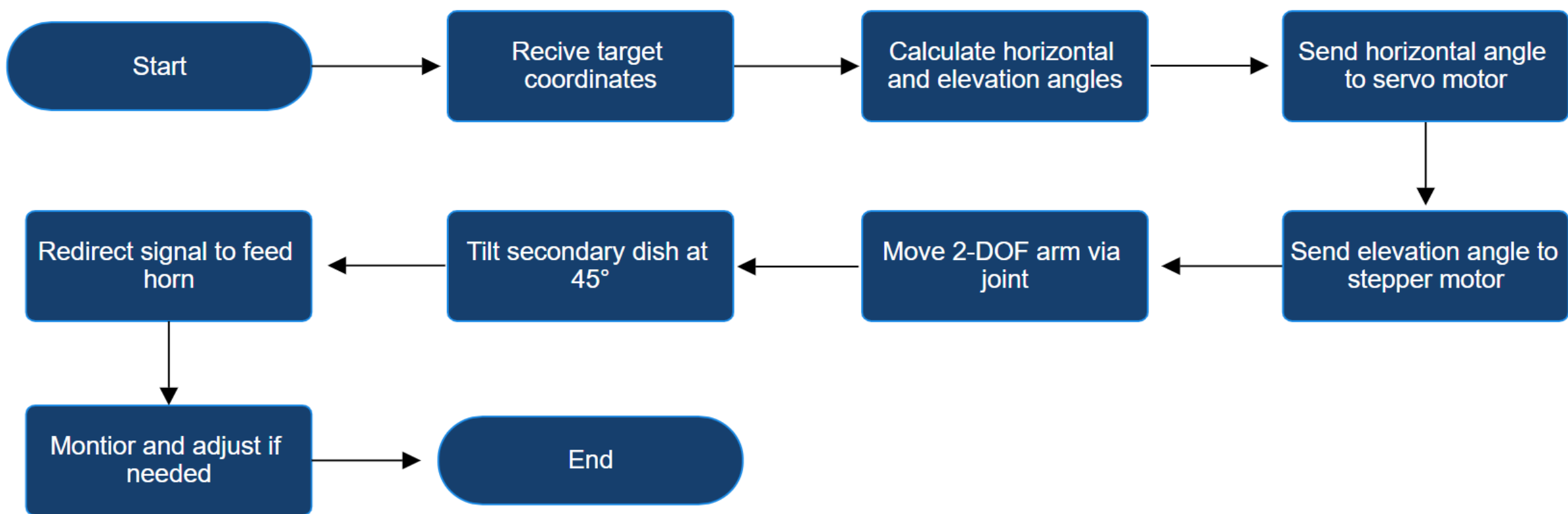
- A servo motor for azimuthal rotation control, providing precise horizontal tracking across the sky.
- A stepper motor for elevation adjustment, allowing vertical fine-tuning of the reflector's angle.
- A spherical joint assembly that enables smooth two-axis rotational motion while maintaining structural stability.
- A secondary feed horn antenna fixed at the system's focal point to capture redirected signals efficiently.

The mesh structure of the movable reflector minimizes wind resistance and aperture blockage, preserving the signal quality and structural integrity. The system was modeled using mechanical design and control theories inspired by existing large telescope steering mechanisms, such as the cable-driven parallel system used in the FAST Telescope and adaptive optics approaches seen in modern reflector designs.

Simulation studies were conducted to assess:

- The increased sky coverage before and after integrating the movable mirror.
- The dynamic behavior of the 2-DOF arm under different tracking scenarios.
- The effectiveness of the steering system in maintaining signal alignment during object tracking.

Through this approach, the system provides extended sky coverage, improved signal collection efficiency, and the ability to dynamically track celestial objects without the need for repositioning the heavy primary dish.



System Operation Flowchart

Proposed Design

The proposed solution is to enhance the performance of the fixed 5-meter radio telescope by installing a lightweight movable mesh parabolic mirror above the main dish.

This secondary mirror is mounted on a 2-degree-of-freedom (2-DOF) mechanical arm, capable of 360° azimuthal rotation and adjustable elevation tilt, controlled by precision servo and stepper motors.

The movable mirror redirects incoming radio signals toward a dedicated secondary feed horn while maintaining a fixed main structure.

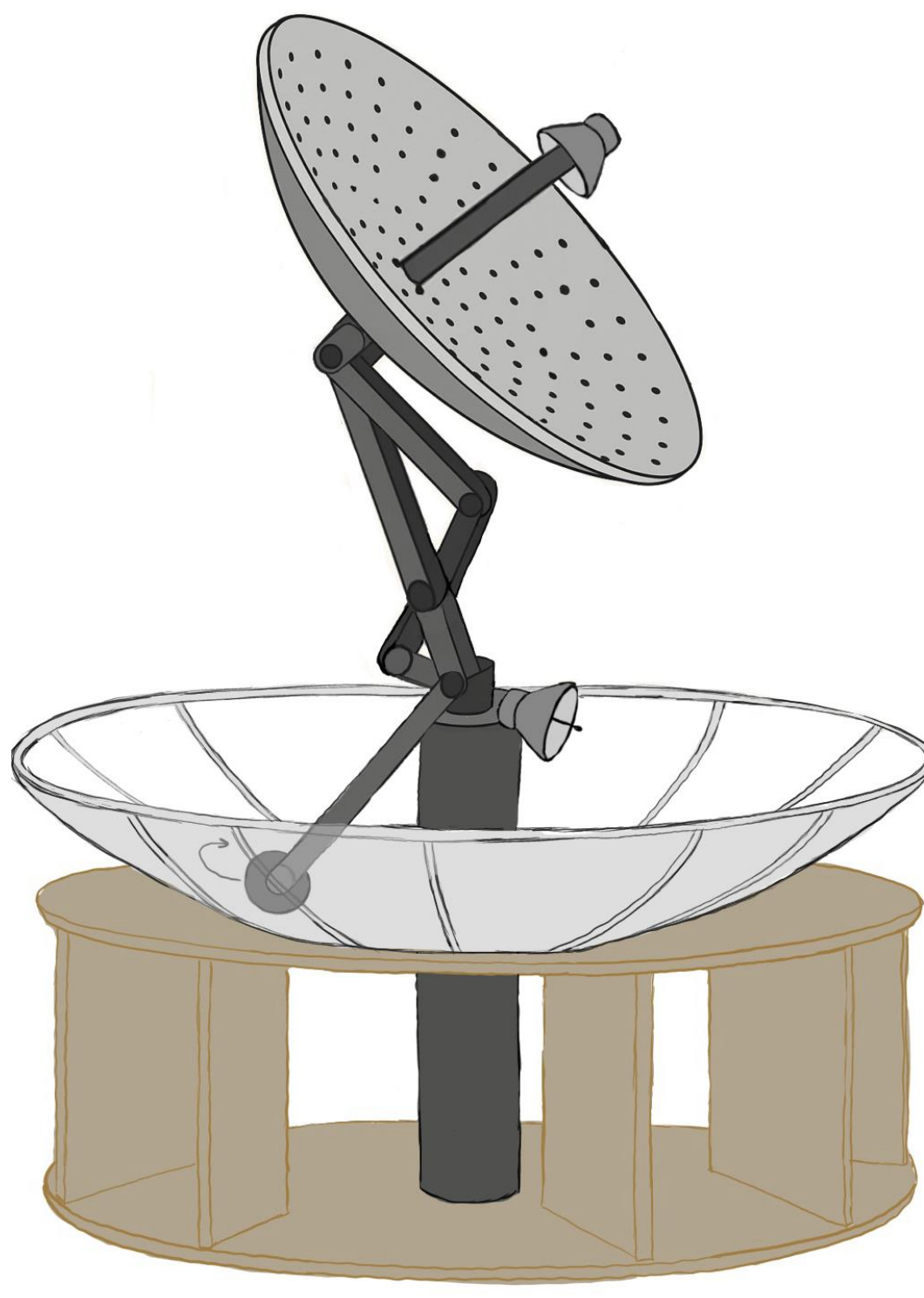
The mesh design of the secondary reflector minimizes wind resistance and reduces blockage of the primary dish’s aperture.

This approach increases the telescope’s field of view, enables continuous tracking of celestial objects, and enhances the overall signal strength received.

By dynamically adjusting the mirror’s orientation, the system can efficiently scan larger areas of the sky without needing to reposition the heavy 5-meter dish, providing greater flexibility and improved observational capabilities.



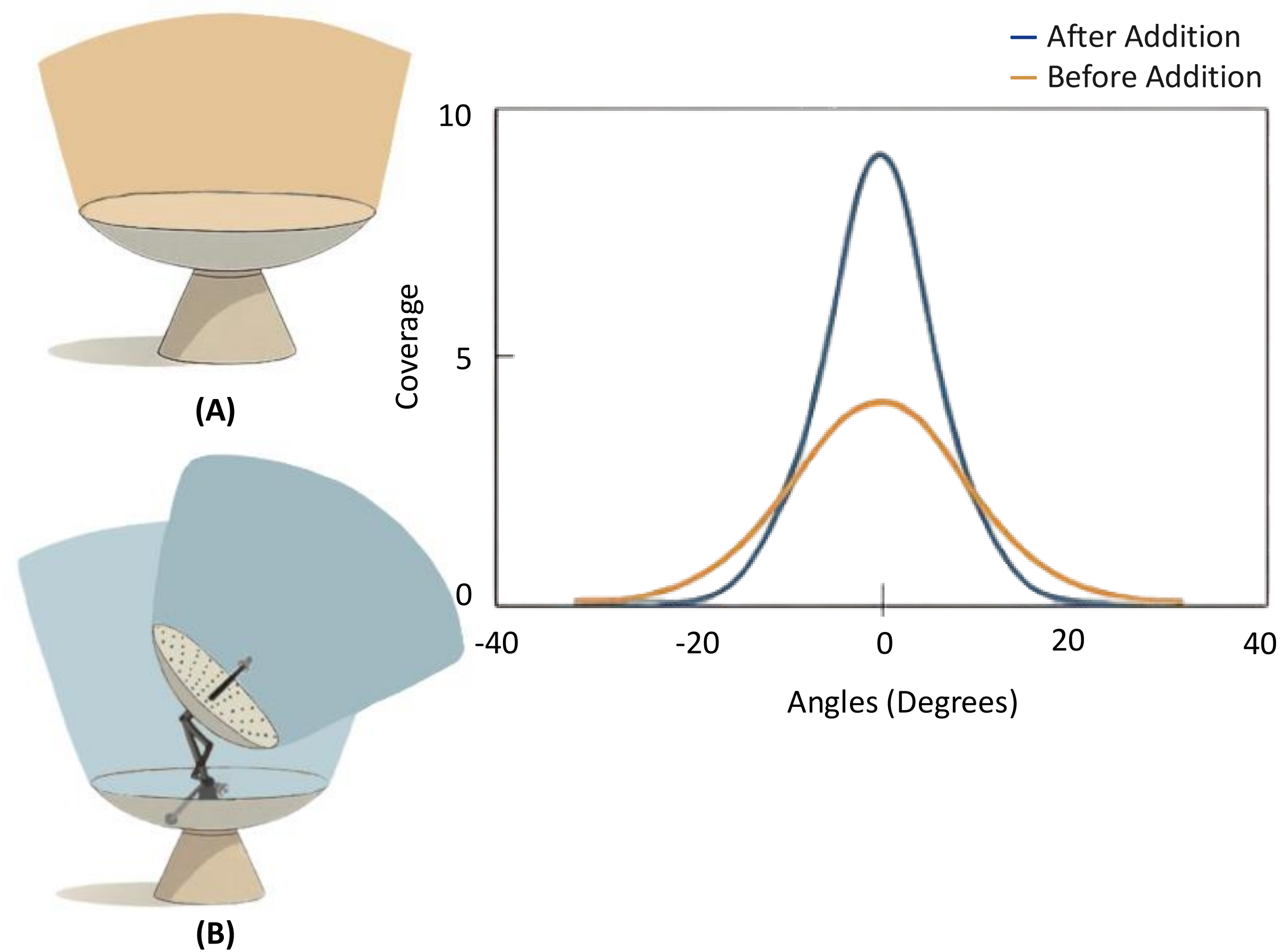
Proposed System (Modeled) for 2-DoF



Proposed System (Modeled) for 3-DoF

Simulation Results

After adding the movable reflector to the existing fixed radio telescope, coverage of the sky is increased while maintaining good signal strength. Sources can now be tracked across a wider area.



Sky Coverage for (A) Before Addition, (B) After Addition

Conclusion

This telescope successfully expands the observational capabilities of the fixed 5-meter radio telescope at Princess Noura University, by incorporating a lightweight secondary parabolic mesh mirror system, mounted on a two-degree-of-freedom (2-DOF) arm. By enabling dynamic tracking of celestial objects without increasing the dish’s diameter, the design significantly enhances sky coverage and maintains signal alignment . The simulation results confirm the effectiveness of the system in maintaining signal alignment and stability.

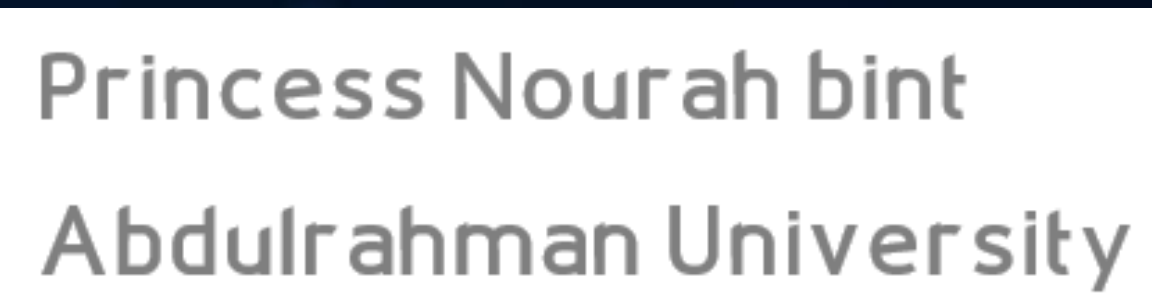
Future developments will focus on the mirror system by integrating an intelligent control unit capable of automatically tracking celestial objects using algorithms based on astronomical databases, allowing the mirror to adjust its orientation toward targeted bodies in real time.

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