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A Hardware-in-the-Loop Star Tracker Test Bed

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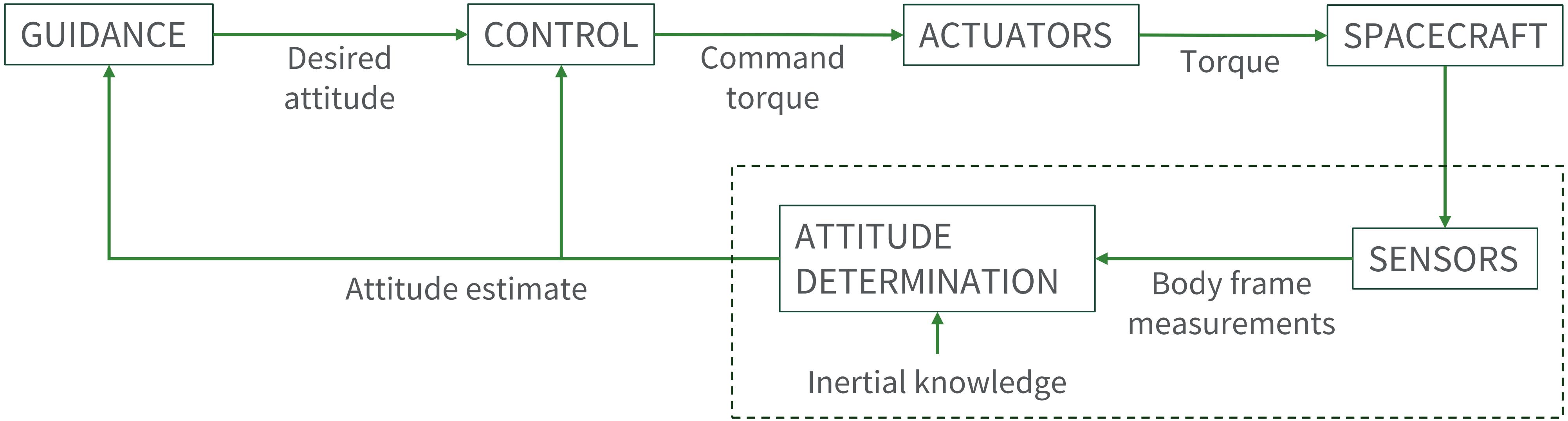
Agenda

- Introduction
- Current Works
- Project Proposal
- Logistics
- Questions

Spacecraft Attitude Determination

Introduction

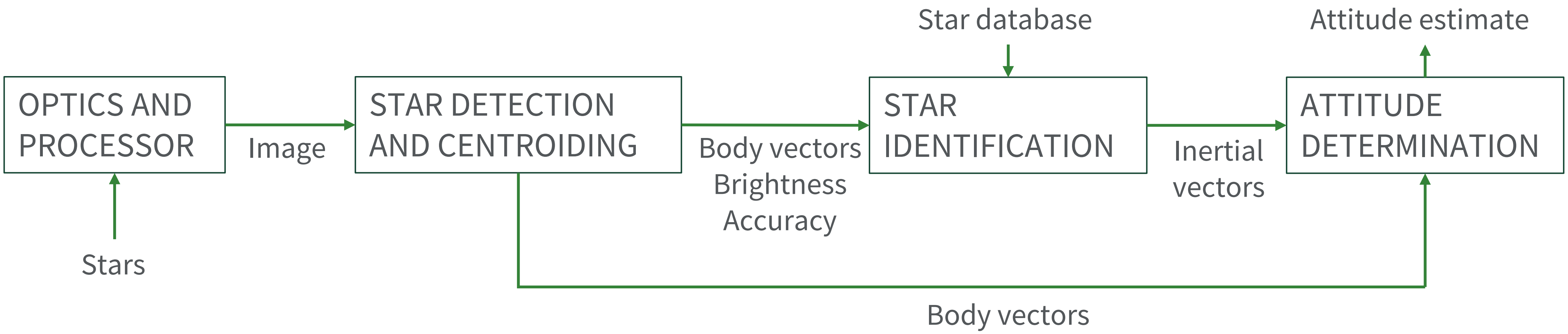
- Many space missions require a high degree of pointing accuracy, which means the spacecraft attitude must be estimated on-board
- Attitude determination is the subset of attitude determination and control that focuses on gathering measurements from spacecraft sensors and combining those with inertial knowledge sources to produce an attitude estimate



Star Trackers

Introduction

- Star trackers are the most accurate attitude sensors, able to provide an accuracy on the order of arcseconds
- By observing multiple stars, three axis attitude knowledge can be determined with just one star tracker
- Inertial data is determined by matching detected stars to stars stored in an on-board star database, generated from a star catalog [1]



Adapted from [2]

Determination Methods

Introduction

- Wahba's problem parameterizes the attitude determination problem as a least squares minimization problem that finds the best estimate of the rotation matrix from the set of inertial frame vectors to the set of body frame vectors [3]
- Triaxial Attitude Determination (TRIAD) [1]
  - Uses only two measurements and does not allow for arbitrary weighting, but computationally simple
  - Returns a rotation matrix
- Quaternion Estimator (QUEST) [1]
  - The most widely used algorithm for solving Wahba's problem
  - Based on Davenport's q Method, which reparametrizes Wahba's problem as an eigenvalue maximization problem
  - Creates a quadratic equation for the eigenvalues to improve computational efficiency
  - Returns a quaternion
- Singular Value Decomposition (SVD) [4]
  - Similar to TRIAD, it generates a rotation matrix, but allows for more than two measurements and arbitrary weighting of those measurements

Hardware-in-the-Loop Testing

Introduction

- Because space missions are costly and have very high reliability requirements, components and systems must be extensively tested on the ground before they are ever launched
- Hardware-in-the-loop testing is used to show how the real hardware responds to simulated input
- Star tracker manufacturers typically provide still images to test their devices, but this does not allow for the testing of other attitude positions or slews
- For full ground-based testing, an entire star field would be simulated for the star tracker to observe
- The star tracker and attitude determination algorithms used to convert the star tracker data to a quaternion must also be tested, and can be used with the real hardware response to simulated input

Low-Cost Star Trackers

Current Works

- Much work in the literature has been done towards the development of low-cost star trackers for small satellite and CubeSat missions, as the cost of commercial star trackers can be prohibitive, and the next best sensor has performance an order of magnitude worse
- These systems use commercial off-the-shelf components and microcomputers

Developer	Image Sensor	Pixel Type	Resolution (px)	Star Identification	Attitude Determination
CPCL [5]	OV3642	CCD	2048x1536	Angular	QUEST
TSL [6]	M121G	CCD	1024x768	Pyramid	SVD
SPEL [7]	Raspberry Pi Camera V2.1	CMOS	3280x2464	Source Extractor/ Match	Not reported
Sarvi, et al. [8]	MP9P031	CMOS	752x480	Pyramid	QUEST

Star Field Simulators

Current Works

- Hemispherical dome with LEDs to simulate a star field [9]
  - Pros: curvature of the dome means every “star” is viewed at the same distance
  - Cons: star database must be generated in reference to the placement of LEDs on the dome
- Screen with collimating lens to display a generated image of a star field [10, 11, 12, 13]
  - Pros: real star catalog data can be used to generate the image
  - Cons: noise effects must be introduced at the image generation level to provide high-fidelity input

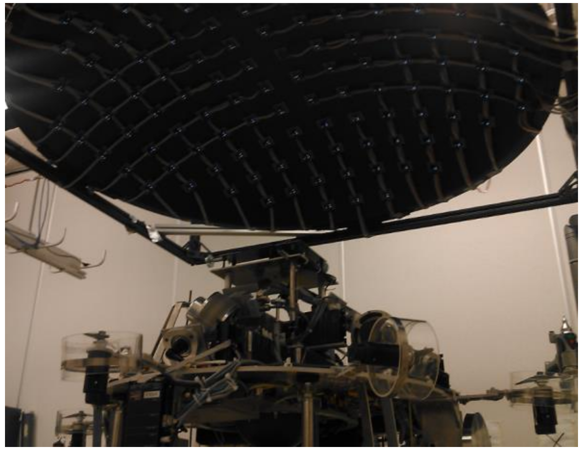


Image source: [9]

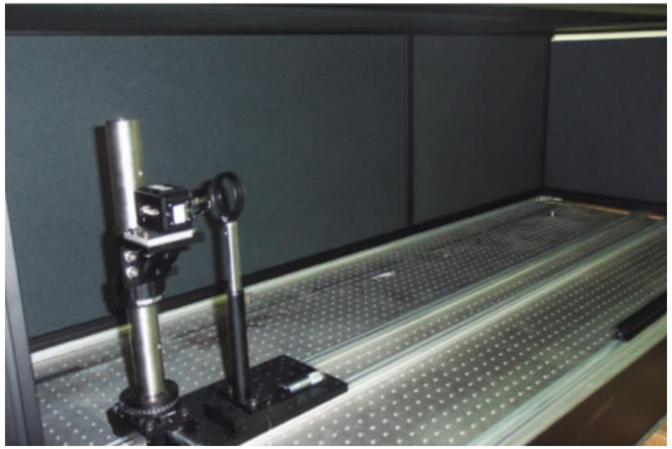


Image source: [11]

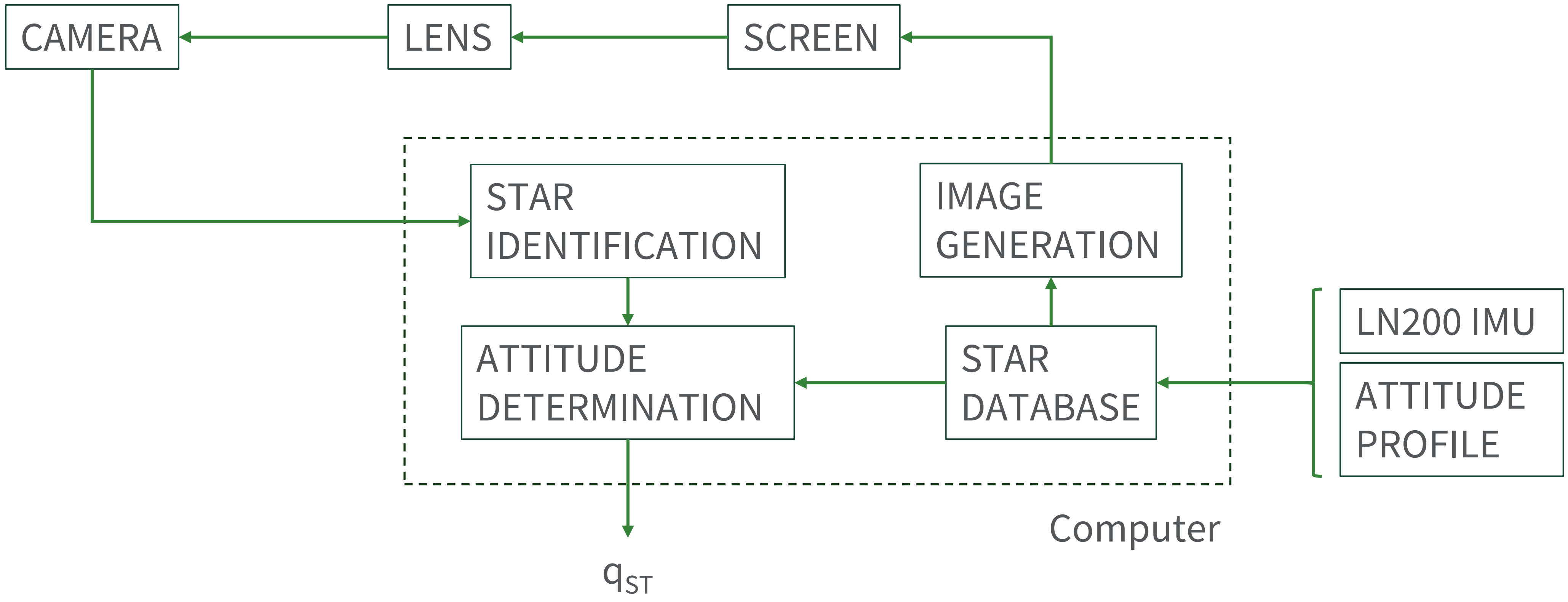
Thesis Statement

Project Proposal

Star trackers are advanced methods of spacecraft attitude determination that require extensive testing of both their hardware and software. The development of a hardware-in-the-loop star tracker test bed will allow for the testing of image filtering algorithms and attitude determination algorithms, as well as any star tracker hardware. The system will consist of a simulated star field, a simple star tracker, and the software algorithms necessary to support system operation.

System Diagram

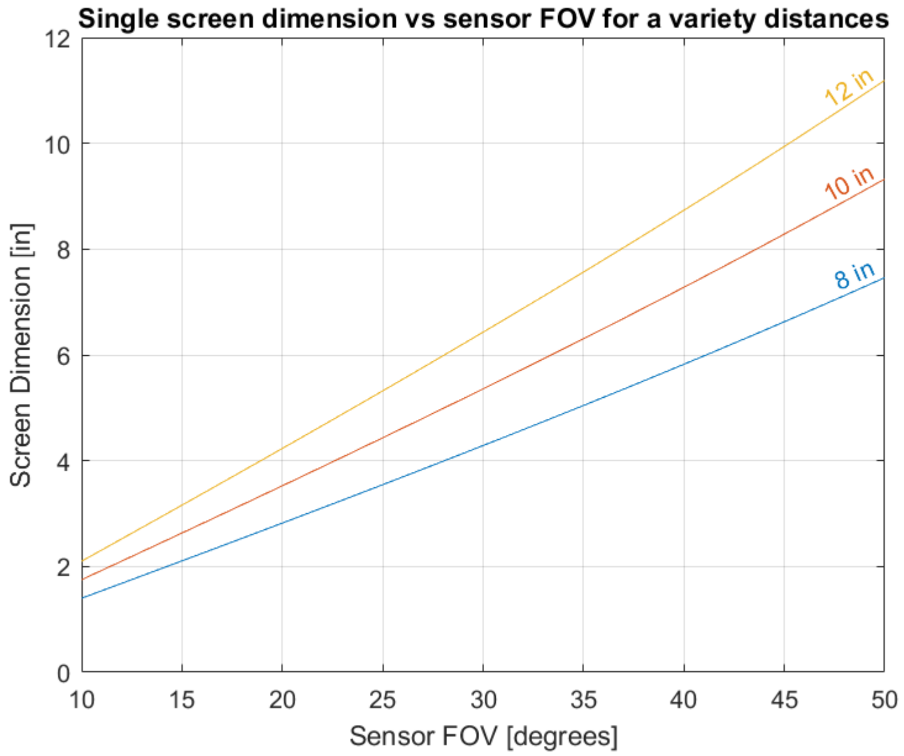
Project Proposal



Hardware

Project Proposal

- Camera
  - Small, on chip sensor
  - Desired field of view in range 10-50 degrees
- Screen
  - Size dependent on sensor field of view and desired distance between screen and sensor
- Computer
  - Raspberry Pi or similar
- Collimating lens
  - Requires more research
  - Focal length dependent on other features of optical system



Software

Project Proposal

- Star Database
  - Hipparcos Star Catalog used to generate the displayed star field images and the "on-board" database for the star tracker algorithms
  - Involves selecting which stars to include and suppling pattern matching information for those stars
- Image Generation
  - Use provided attitude data to generate a star field to display based on the star catalog
- Star Identification
  - Utilize OpenCV, an open source computer vision library, to assist in image filtering
  - Generate the matching data sets and perform a database search
- Attitude Determination
  - QUEST algorithm to produce an attitude quaternion, as it is the most commonly used with star trackers

Attitude Sources

Project Proposal

- Litton LN-200 IMU
  - Donated IMU from Northrop Grumman
  - Supplies accelerometer and gyro data
  - Can provide a “true” attitude for input into the image generation algorithm
  - Less interesting when the test bed is sitting on a table, more interesting once it is integrated into the Pyramidal Reaction Wheel Platform (PRWP)
- Attitude profile
  - Use MATLAB/Simulink to generate an attitude profile (normal on-orbit operations, slew, detumble, etc.)
  - Input the generated attitude profile into the image generation algorithm
  - Can test star tracker response to situations that are not possible to represent on the PRWP

Pyramidal Reaction Wheel Platform

Project Proposal

- Cal Poly's Pyramidal Reaction Wheel Platform (PRWP) is an air bearing spacecraft simulator used to test and verify control laws
- It has been contributed to by many master's theses, with the most recent updates in 2014
- The current attitude determination and control system uses the LN-200 IMU, CRS03 MEMS gyroscopes, and reaction wheels
- Integration of the proposed system will allow for the investigation of a variety of attitude determination algorithms in addition to the current capability of control law testing
- Two concurrent master's theses are working on updating the PRWP, so integration may not be feasible this year

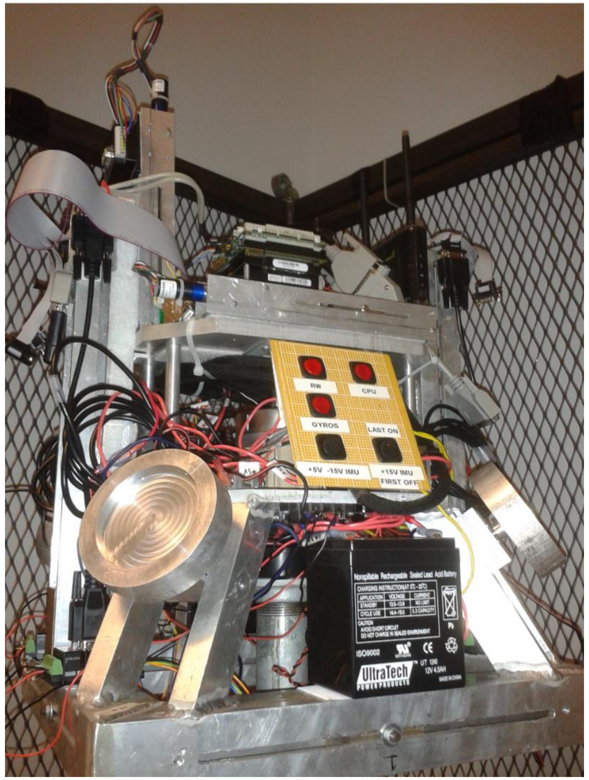


Image source: [14]

Project Goals

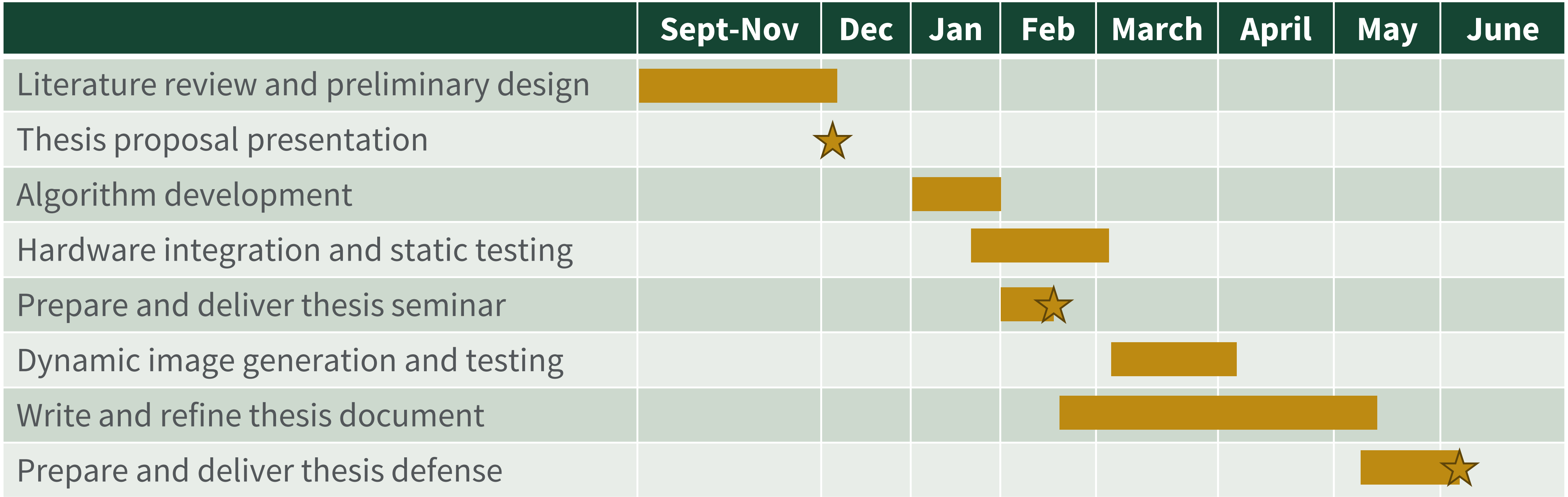
Logistics

- Primary – completion of the proposed system
- Secondary – increasing system fidelity (one or more of the following)
  - Image generation – adding additional noise sources
  - Star identification – writing more of the star detection code by hand, implementing an additional star identification algorithm for testing
  - Attitude determination – implementing an additional attitude determination algorithm for testing
- Bonus – integration with the PRWP
  - Pending completion of concurrent theses

- What the goal is not
  - Developing a flight ready low-cost star tracker
  - Creating a high-fidelity image generation system
  - Complete testing and verification of a control system

Proposed Schedule

Logistics



Risk and Contingency Plan

Logistics

- Hardware availability
  - Place orders before winter break
  - Have backup hardware options since project does not depend on hardware specifics
- Hardware failure
  - Potentially purchase duplicates, budget pending
- Inability to complete in accordance with schedule
  - Delayed defense

Questions?

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