Computer Aided Medical Procedures

Project Checkpoint
Robotic Ultrasound Needle Placement and Tracking: Robot-to-Robot Calibration

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Background

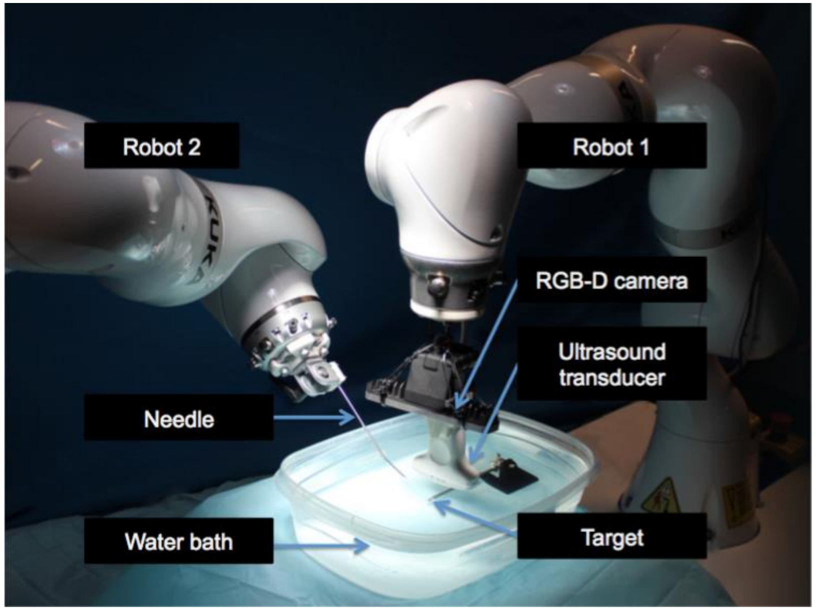
In medicine and industry[7], there is a need for flexible multi-robot platforms that allow for independent placement of multiple robotic manipulators.

Background

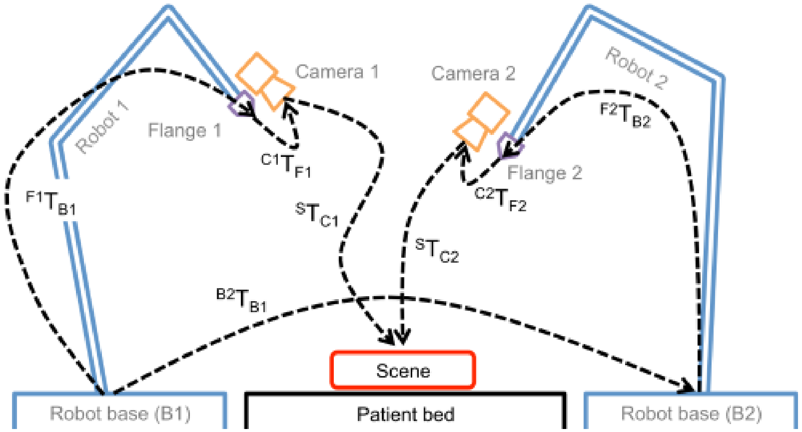
- CAMP lab has designed a novel multi-robot platform.
- This mobile platform provides flexibility in the operating room environment.
- For multi-robot surgical procedures, precise coordination is key.
- Base to base calibration must be done frequently, because the platform is mobile.
- We need an efficient method to precisely calibrate multiple robots.

Objective

Explore a variety of robot-to-robot calibration methods and validate their efficacy for use in dual-robotic surgeries and experiments.



From *Dual-Robot Ultrasound-Guided Needle Placement* [5]



$$^{B2}T_{B1} = {}^{F2}T_{B2}^{-1}\ {}^{C2}T_{F2}^{-1}\ {}^{S}T_{C2}^{-1}\ {}^{S}T_{C1}\ {}^{C1}T_{F1}\ {}^{F1}T_{B1}$$

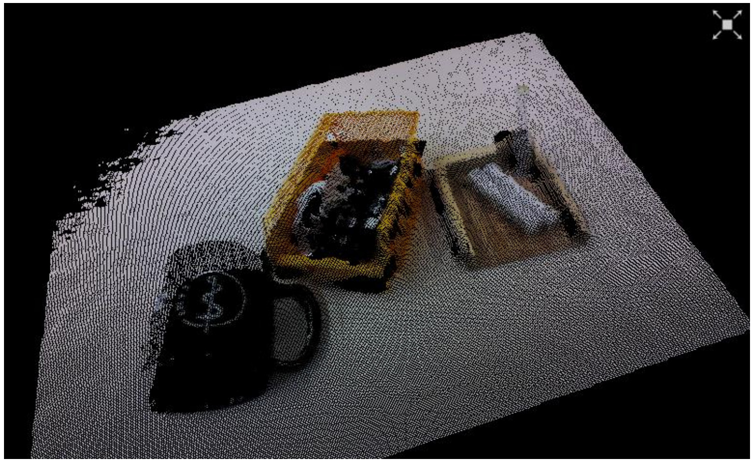
Plan Overview

1. Checkerboard Calibration

2. Visual Marker Tracking Calibration

3. RGB-D Features and Depth

4. RGB-D Depth-Only



Dependencies

Type	Dependency	Status
Hardware	KUKA iiwa Dual Robotic System	✓
	3D-Printed Intel Camera Mounts	✓
	Access to Mock OR and Robotorium	✓
	Calibration Checkerboard	✓
	ARToolKit Markers	✓
	Feature Calibration Objects	✓
	Improve KUKA Pointer	Mentor
Software	ImFusion, PCL, ARToolKit	✓
	KUKA Sunrise	✓
	Intel RGB-D Camera SDK	✓
Other	Risto's Needle Tracking Algorithm	✓
	Tissue Sample for Ultrasound Testing	Mentor or Butcher

Deliverables

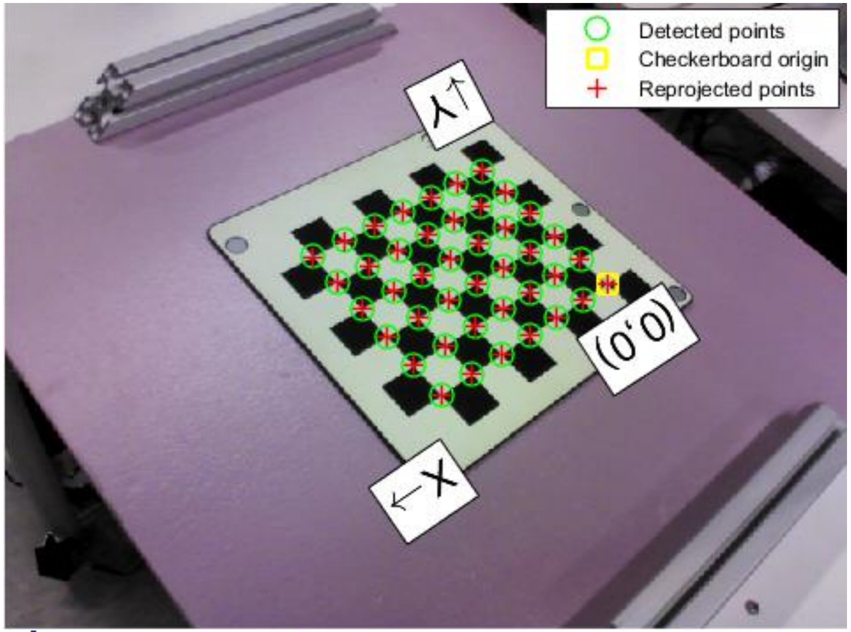
Complete In Progress Low Priority

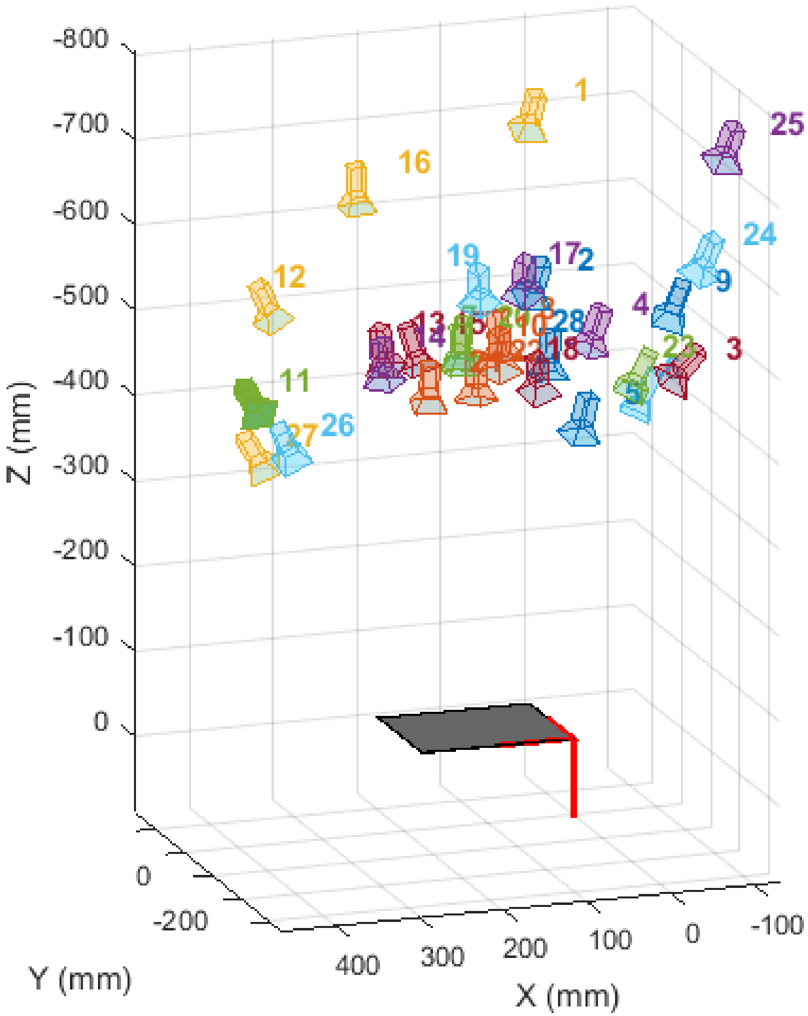
Minimum	Fully documented hand-eye calibration program that produces the transformation from a rigidly attached camera to the robot's end-effector, ${}^{g}H_{e}$
	Fully documented checkerboard calibration program that produces the transformation from the second robot base to the first robot base, ${}^{b1}H_{b2}$
	Validation experiment protocol and report of results
Expected	Fully documented ARToolKit calibration program that produces the transformation from the second robot base to the first robot base, ${}^{b1}H_{b2}$
	Fully documented RGB-D features and depth calibration program that produces the transformation from the second robot base to the first robot base, ${}^{b1}H_{b2}$
	Report of validation experiment results
Maximum	Fully documented RGB-D depth-only calibration program that produces the transformation from the second robot base to the first robot base, ${}^{b1}H_{b2}$
	Report of validation experiment results
	Needle targeting in real tissue experiment results

Camera Calibration

Objective

Given a set of images of a calibration object with known dimensions (i.e. checkerboard), determine the intrinsic and extrinsic matrices of the camera.





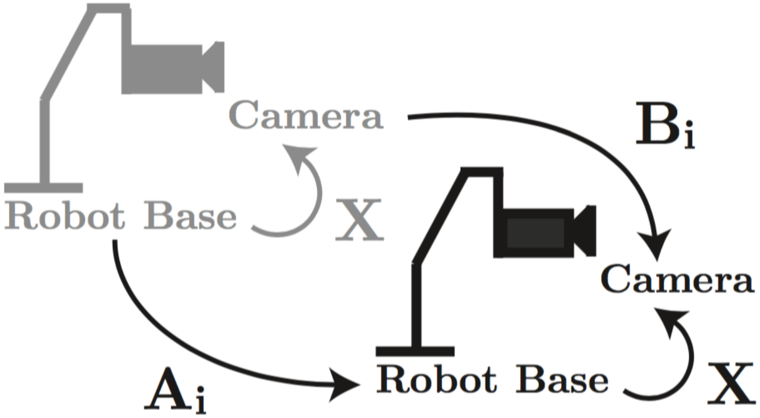
Hand-Eye Calibration

Objective

Given a set of robot calibration states and the corresponding images of a known calibration object, produce the transformation from the camera space to the robot's end-effector space.

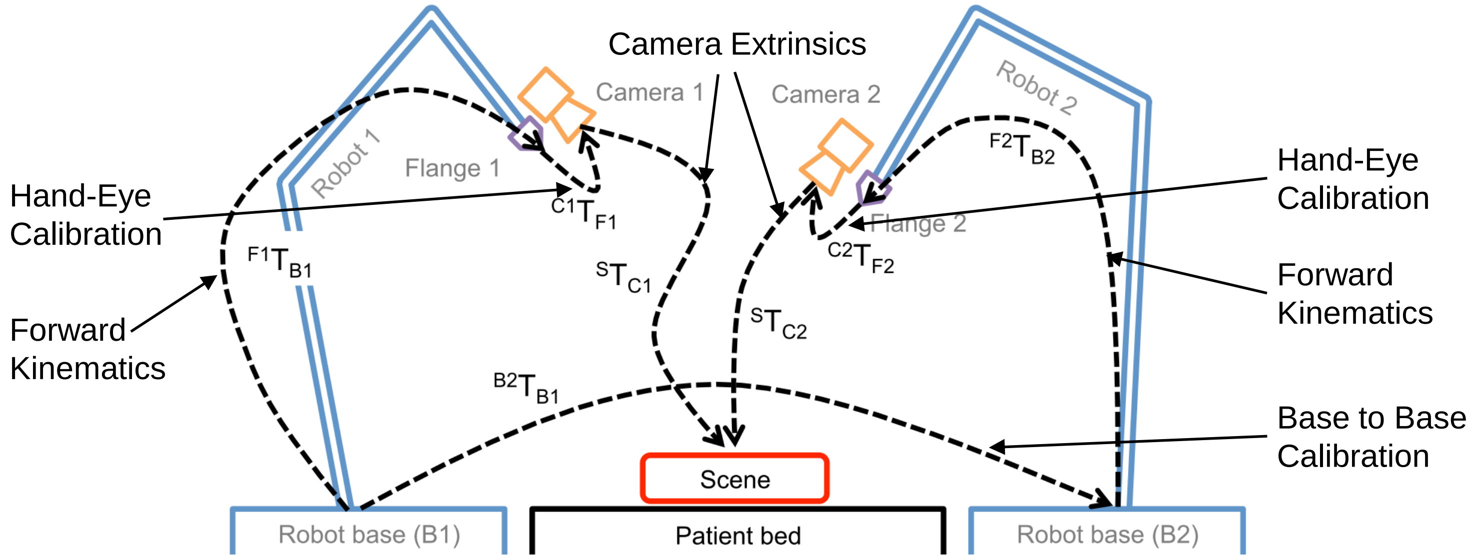
Tsai's Least-Squares Method

1. Command the robot to *N* predefined states. Each state should be oriented such that the camera is facing the calibration object.
2. Acquire a photo of the calibration object at each state.
3. Generate the camera's position relative to the calibration object in each frame.
4. Solve the equation AX = XB, where A is the transformation between camera poses, B is the transformation between robot end effector poses, and X is the transformation ${}^{g}H_{e}$.



From *An Overview of Robot-sensor Calibration Methods for Evaluation of Perception Systems* [3]

Checkerboard Calibration



$$^{B2}T_{B1} = {}^{F2}T_{B2}^{-1}\ {}^{C2}T_{F2}^{-1}\ {}^{S}T_{C2}^{-1}\ {}^{S}T_{C1}\ {}^{C1}T_{F1}\ {}^{F1}T_{B1}$$

Pseudo-Code

```
Input: sq_sz, jerry_files, dash_files
    [g1He1, b1Hw] = calibrate_handeye( jerry_files, sq_sz )
    [g2He2, b2Hw] = calibrate_handeye( dash_files, sq_sz )
    b1Hb2 = b1Hw * b2Hw^-1
Output: b1Hb2
```

Calibration Error Analysis

Protocol

1. Manually position robots so calibrated pointer tips are touching. These points have zero linear distance between them and are considered the ground truth.
2. Transform the second robot's points into the first robot's base frame.
3. Measure the Euclidean distance between the point pair as the linear error.
4. Repeat this process at many points around the robots' workspace.

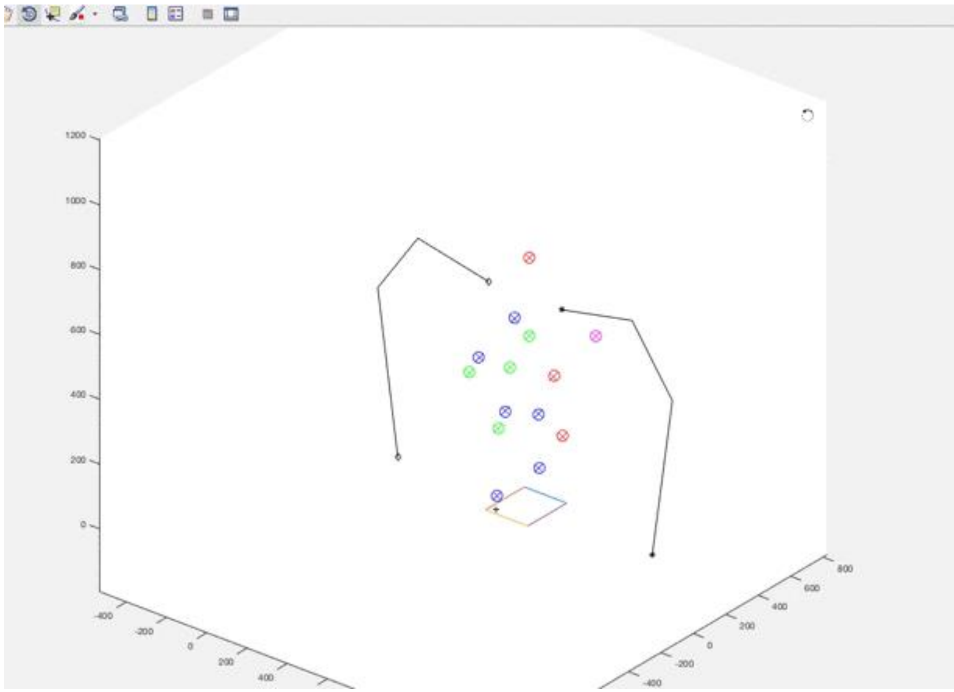
Optional

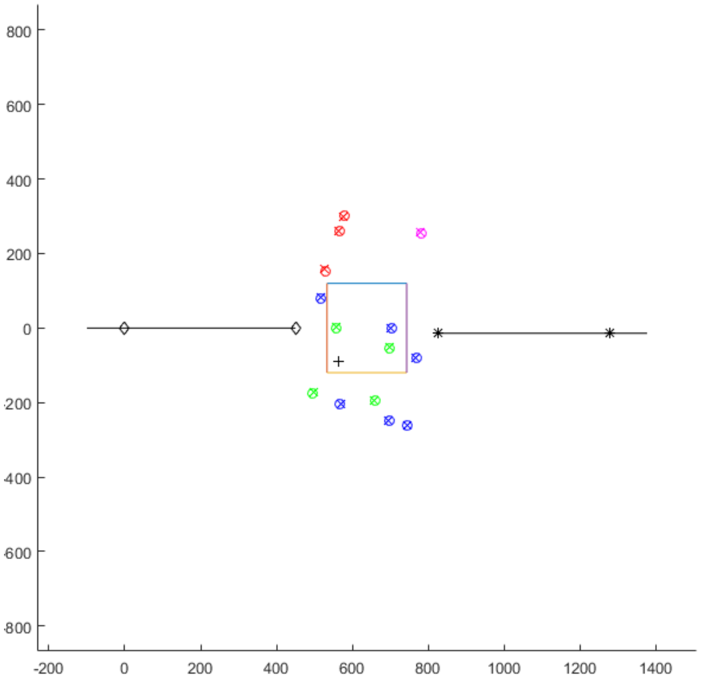
To get Z-axis rotation error, compute tangential error component for each point and divide by distance from workspace center.

Calibration Error Results

Mean Linear Error: 2.7599 mm
StDev: 1.1598 mm

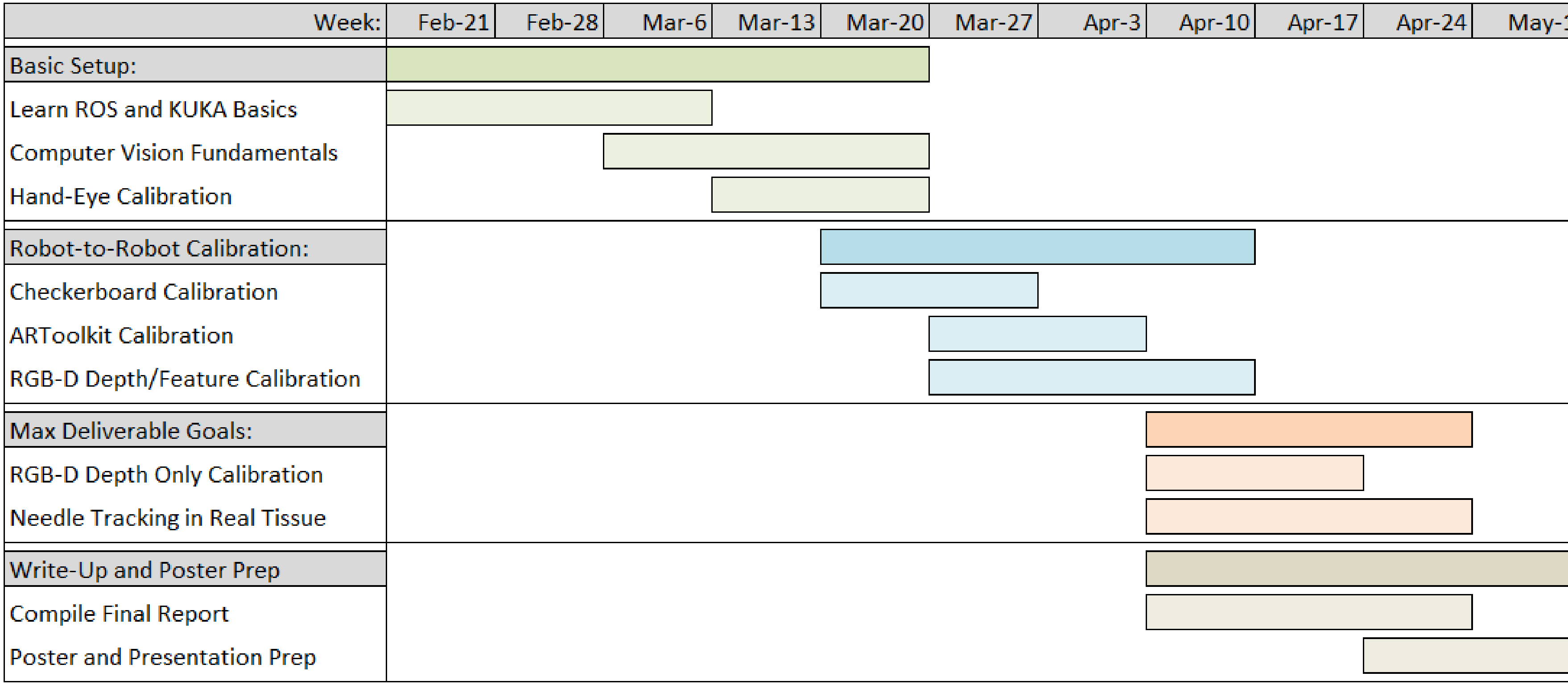
Mean Z-Axis Rotation Error: 0.7448˚
StDev: 0.4583˚





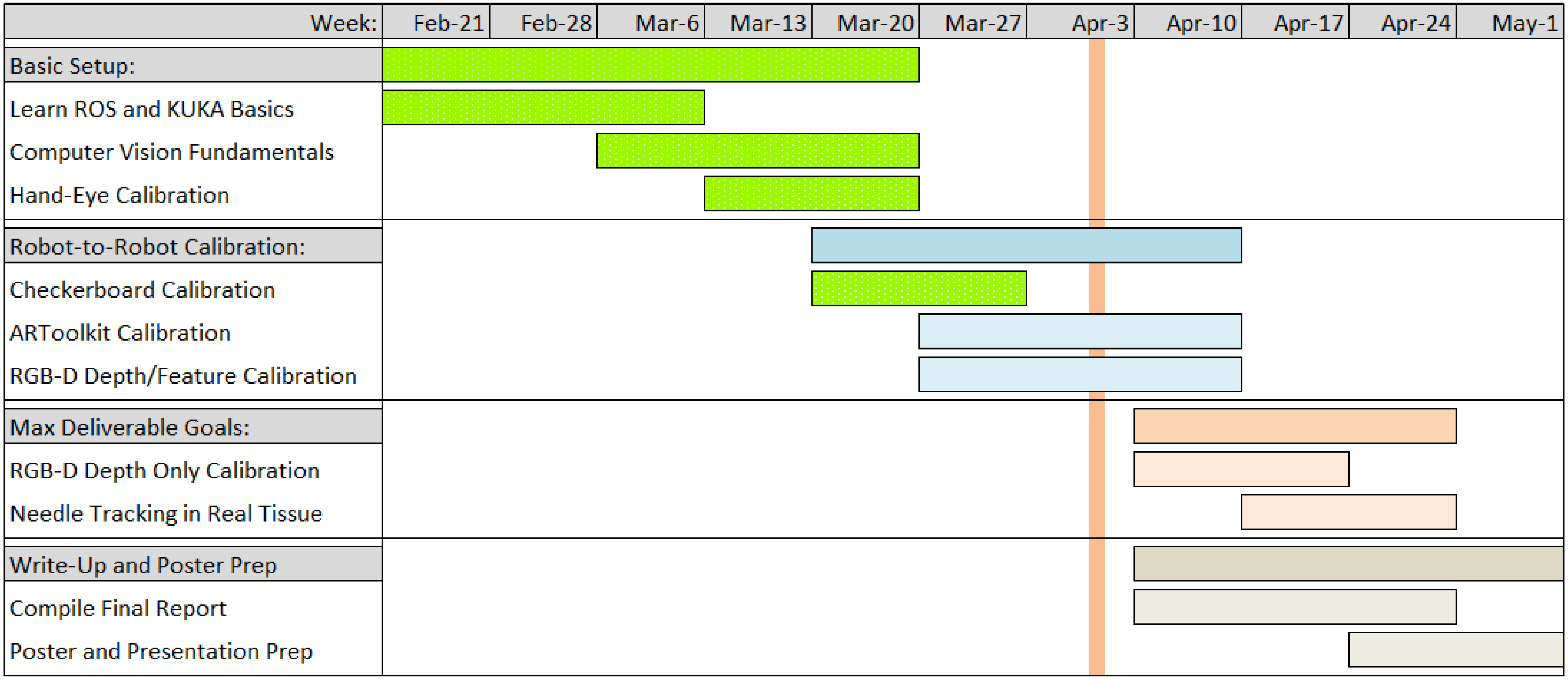
- Linear Error < 2mm
- Linear Error < 3mm
- Linear Error < 4mm
- Linear Error < 5mm

Time Table



Week:
Feb-21
Feb-28
Mar-6
Mar-13
Mar-20
Mar-27
Apr-3
Apr-10
Apr-17
Apr-24
May-1
Basic Setup:
Learn ROS and KUKA Basics
Computer Vision Fundamentals
Hand-Eye Calibration
Robot-to-Robot Calibration:
Checkerboard Calibration
ARToolkit Calibration
RGB-D Depth/Feature Calibration
Max Deliverable Goals:
RGB-D Depth Only Calibration
Needle Tracking in Real Tissue
Write-Up and Poster Prep
Compile Final Report
Poster and Presentation Prep

Time Table - Revised



Upcoming Checkpoints

- April 12th: Maximum Deliverables Research
- April 16th: ARToolKit Calibration Program
  RGB-D Features and Depth Program
- April 23rd: RGB-D Depth-Only Program

Readings

1. B. Fuerst, J. Fotouhi, and N. Navab. **"Vision-Based Intraoperative Cone-Beam CT Stitching for Non-overlapping Volumes."** *Lecture Notes in Computer Science Medical Image Computing and Computer-Assisted Intervention -- MICCAI 2015* (2015): 387-95. Web.

2. H. Bay, T. Tuytelaars, and L. Van Gool. **"SURF: Speeded Up Robust Features."** Computer Vision – ECCV 2006 Lecture Notes in Computer Science (2006): 404-17. Web.

3. M. Shah, R. D. Eastman, and T. Hong. **"An Overview of Robot-sensor Calibration Methods for Evaluation of Perception Systems."** Proceedings of the Workshop on Performance Metrics for Intelligent Systems - PerMIS '12 (2012). Web.

4. O. Zettinig, B. Fuerst, R. Kojcev, M. Esposito, M. Salehi, W. Wein, J. Rackerseder, B. Frisch, N. Navab, **"Toward Real-time 3D Ultrasound Registration-based Visual Servoing for Interventional Navigation,"** IEEE International Conference on Robotics and Automation (ICRA), Stockholm, May 2015.

5. R. Kojcev, B. Fuerst, O. Zettinig, J.Fotouhi, C. Lee, R.Taylor, E. Sinibaldi, N. Navab, **"Dual-Robot Ultrasound-Guided Needle Placement: Closing the Planning-Imaging-Action Loop,"** Unpublished Manuscript.

6. R. Tsai, and R. Lenz. **"A New Technique for Fully Autonomous and Efficient 3D Robotics Hand/eye Calibration."** IEEE Trans. Robot. Automat. IEEE Transactions on Robotics and Automation 5.3 (1989): 345-58. Web.

7. Y. Gan, and Xong Dai. **"Base Frame Calibration for Coordinated Industrial Robots."** Robotics and Autonomous Systems 59.7-8 (2011): 563-70. Web.

Questions?