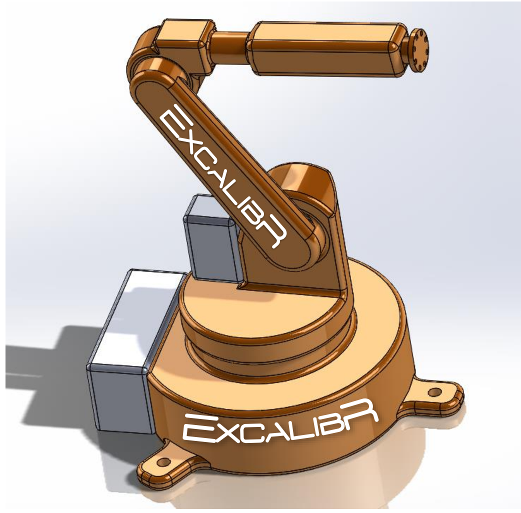

EXCALIBR

ROBOTIC CALIBRATION OF MULTI-SENSOR CAPTURE SYSTEM

CONCEPTUAL DESIGN REVIEW : 09/30/2016

TEAM G

Haun-Yang Chang (Peter)
Man-Ning Chen (Mandy)
Sambuddha Sarkar (Sam)
Siddharth Raina (Sid)
Yiqing Cai (Cece)

SPONSOR

oculus

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1. Project description

1.1 Project Details

Oculus Research, Pittsburgh is building a multi-sensor capture system consisting of a large number of cameras and microphones to perform motion tracking and 3D reconstruction of unprecedented precision. The capture system consists of a dome, 11 ft. in diameter, mounted with the sensors required for capturing images and sound.

The first step for achieving this goal of motion tracking and 3D reconstruction involves accurate calibration of the sensors. The scope of the project involves calibrating these sensors accurately using a robotic arm and an engineered calibration target. The calibration target would be attached to the end effector of the robotic arm, which would move around in the capture system and calibrate the sensors attached to the capture space.

The calibration process would involve four methods, namely: geometric calibration of the cameras, estimation of the illumination: light field calibration, photometric calibration of the cameras and acoustic calibration of the microphones.

1.2 Project Goals

To design a turnkey solution for robotic multi sensor calibration of a capture space consisting of a large number of cameras and microphones, with an accuracy of less than 10 microns and a rotational accuracy of less than an arc second.

2. Use Case

2.1 Narrative

After the meeting with the customer, Peter was very depressed because of the complains about the quality of the 3D reconstruction which were haunting his mind. Peter was a hard worker and usually stayed up late for calibrating the system in order to maintain the system's accuracy for the next day's work. However, using the manual checkerboard method could only give him a coarse result. Besides, the huge number of cameras and microphones to be calibrated left him totally drained out of energy. In the midnight, he started to think if there was a system which could help him to autonomously calibrate this multi-sensor system.

One-day Peter found out a new machine had been installed in the office. This new calibration system, called 'Excalibr' could calibrate cameras and microphones autonomously and had an amazing accuracy. At last, Peter didn't have to stay up all night and would just push a button to calibrate the sensors. The calibration system would finish its job autonomously throughout the night with excellent quality. A happier ending than most Disney stories.

3. System Level Requirements

Table 3.1

MANDANTORY SYSTEM LEVEL REQUIREMENTS	DESIRABLE SYSTEM LEVEL REQUIREMENTS
Functional Requirements: M.F.1: Fabricate calibration target M.F.2: Fix light source M.F.3: Control and manipulate the calibration target M.F.4: Emit sound with a frequency sweep M.F.5: Take high-resolution, stable and clear pictures of calibration target M.F.6: Implement camera calibration algorithms on cameras mounted on the dome M.F.7: Calibrate the camera on end-effector for light-field calibration M.F.8: Develop audio calibration method M.F.9: Complete tasks efficiently M.F.10: Validate results	**Functional Requirements:** D.F.1: Achieve accuracy standard D.F.2: Operate safely around human
Performance requirements: M.P.1: Fabricate the target with 50 micrometers tolerance M.P.2: Manipulate the robot with 10 micrometers accuracy M.P.3: Take pictures with camera more than 5MP at 50fps M.P.4: Complete one stage calibration in at most 8 hours M.P.5: Emit sounds sweeping the frequency between 82~1200 Hz and intensity between 60~100dB M.P.6: Execute calibration of at least 100 microphones and 140 cameras in the same cycle M.P.7: Capture and store at least 3000 images for one calibration set M.P.8: Avoid collisions - keep a distance 0.3m away from the dome extremities and sensors M.P.9: Complete the whole calibration process in one night - around 12 hours	**Performance requirements:** D.P.1: Fix light source: correct it with a suitable offset ~ 100 microns D.P.2: Warn people when calibrating: sound alarm if human in close proximity of the system D.P.3 Calibrate the cameras on the dome to 10-100 micrometers and 1 arc second D.P.4 Calibrate the camera for light-field on end-effector to 100 micrometer accuracy D.P.5: Develop an audio calibration system with 100 micrometer accuracy D.P.6: Validate before Dec 1 or 8
Non-functional requirements: M.N.1: Operate autonomously	**Non-functional requirements:** D.N.1: Create a user-friendly GUI or physical button

4. Functional Architecture

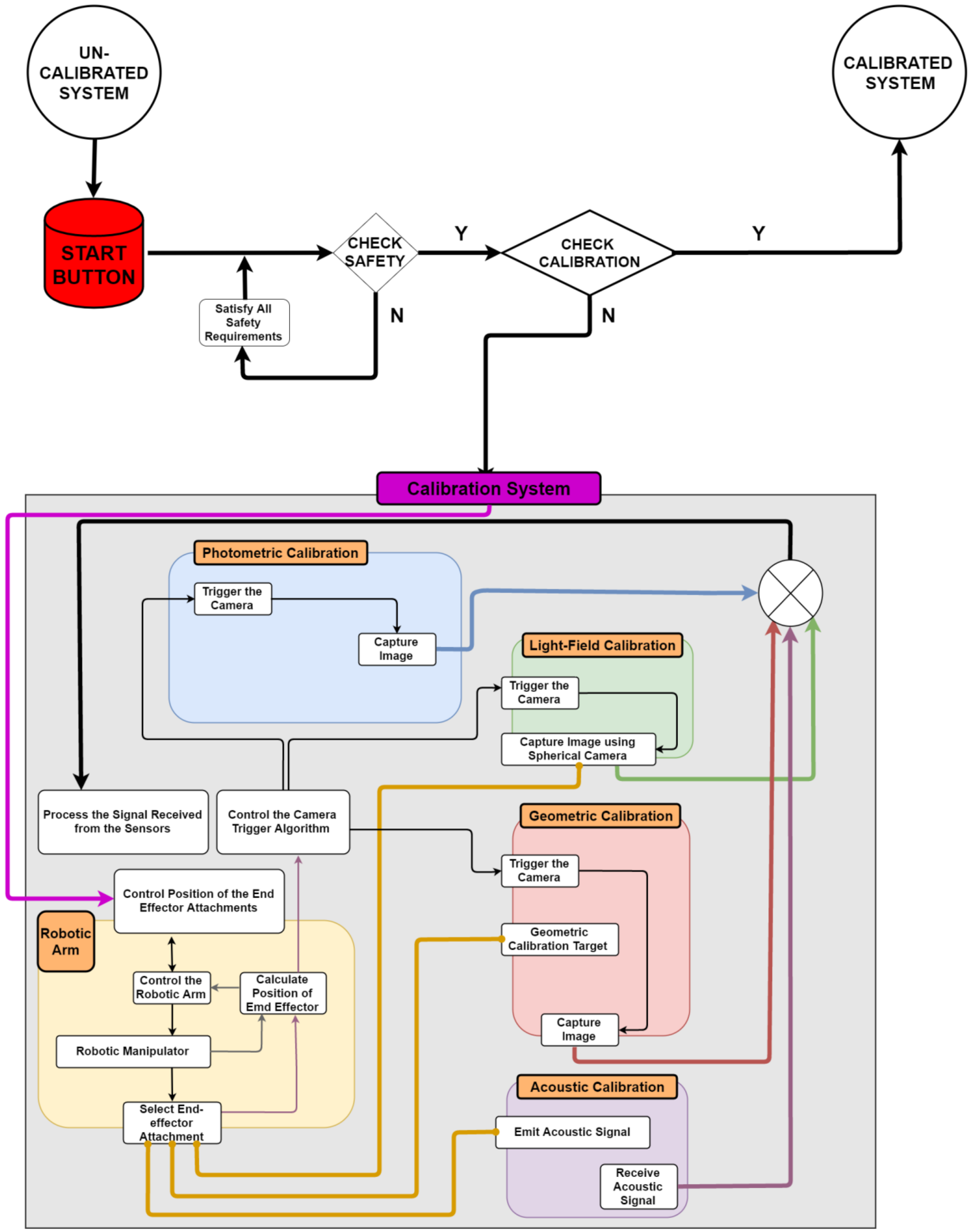


Figure 4.1 Functional Architecture

The flow of the functional architecture can be divided into the following components:

- Geometric Calibration: for geometric calibration, a target would be attached to the end effector of the robotic arm. The position of the calibration target would be calculated using the position encoders mounted on the robotic arm and would be sent back to the controller (for feedback control) and the computer/ access terminal. The access terminal would trigger the cameras based on the position of the calibration target. The camera would capture the image of the target and feed it into the calibration algorithm which would then compute the parameters required for camera calibration. The target can be programmed to move in the following ways:

    - Discrete: The target would move to a position and stop. Then a pulse would be sent to the computer which would trigger the cameras to simultaneously capture images. After the image capture, the computer would send the signal to the controller to move the robotic arm end effector to the next position.
    - Continuous: The target would move continuously, without stopping. As it arrives at a desired position, it would send a pulse to the computer, which would trigger the cameras to capture the images of the target, while the target would be moving. This method is faster than the discrete motion, but may lead to images with motion blur.

- Light Field Calibration: This method would be used to determine the illumination of the desired space. The first step would involve calibration of a spherical camera mounted on the robotic arm and then this spherical camera would be used to calculate the desired illumination.

- Photometric Calibration: This method involves mapping the intensity of light (in lumens) to the corresponding pixel values. This would require images from the geometric calibration and the light field intensity as a function of space in order to calculate the parameters of photometric calibration.

- Acoustic Calibration: This method involves using a speaker to emit a multi frequency variable amplitude sound signal. The microphones situated on the capture space would receive this signal and the two signals (one emitted from the speaker and one received by the microphones) can be compared in order to compute the position of the microphones.

5. System Level Trade Study

The first step of the robotic calibration system involves building the calibration target to evaluate the accuracy. Different types of calibration target designs would influence the process of the whole system.

5.1 Trade Study on size of calibration target

For geometric calibration, the size and position of the calibration target is an important factor. This would directly affect the intrinsic and extrinsic parameters of the camera during calibration. The following table summarizes the design choices, first design (D1) uses a small checker board (length of each face < 3cm), Design 2 (D2) using medium check board (3cm<length in each face <20cm), Design 3 (D3) using medium check board (20cm<length in each face)

Table 5.1 Scoring of 3 Designs for calibration target size (High Score desirable)

	Weight	D1: Small < 3cm	D2: Medium 3cm<X<20cm	D3: Large >20cm
Manufacture	5	5	3	1
Surface Printing	10	10	10	5
Safety	10	7	7	7
Automation	20	15	15	15
Not Complexity	10	10	10	10
Durability	15	10	10	10
Time saving	15	5	13	15
Accuracy	15	10	15	10
Total		72	83	73

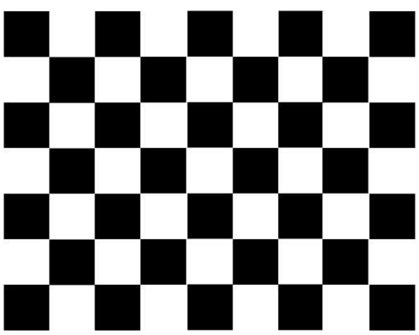


Figure 5.1 Calibration pattern

The selection criteria of the system for trade study is manufacturing ease, surface printing, safety, automation, simplicity, durability, less time for fabrication and accuracy. D1 relatively scores high in manufacturing and surface printing, because the target is small enough we can use the commercial equipment to make it. D1 scores relatively low at time saving because we have more steps that are needed to cover the whole target space. D2 is relatively high at accuracy because the sponsor would want to capture the face in detail. Hence, using a calibration target of similar size would lead to a better result. D3 manufacturing saves a lot of time, but in accuracy

and manufacturing the D3 is relatively low, because the target is harder to manufacture and accuracy is relatively hard to achieve.
Hence we choose D2.

5.2 Trade Study calibration target configuration.

In our calibration system, we have to calibrate the different characteristics of various cameras, environment and microphones. Design 4 (D4) combines all subsystem level calibration targets together into a single calibration target and Design 5(D5) separates the subsystem-level calibration targets to different parts.

Table 5.2: Scoring of 3 Designs for calibration target configuration (High Score desirable)

	Weight	D4: Combined calibration Target	D5: Separated Calibration Target
Manufacture	5	1	3
Safety	10	7	7
Automation	20	20	15
Not Complexity	10	1	5
Durability	15	5	13
Time saving	15	15	10
Accuracy	15	10	13
Total	90	59	66

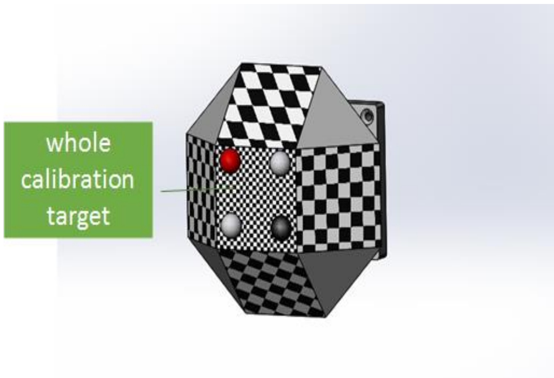


Figure 5.2 D4 (Design 4)

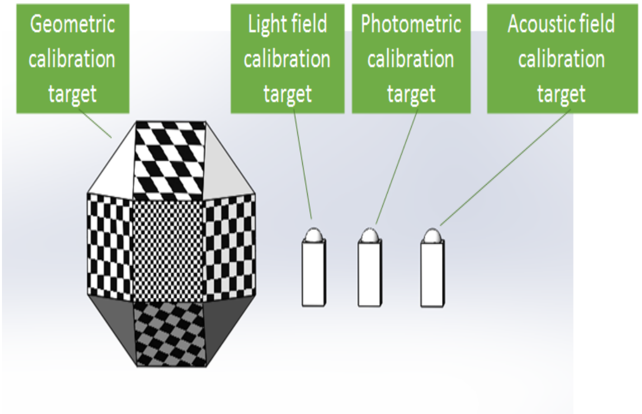


Figure 5.3 D5 (Design 5)

Design 4 is relative high in automation and time saving, because the robot can keep performing different calibrations at the same time which can reduce the time it takes to replace the calibration target every time for each calibration procedure. On the other side, Design 4 is harder to manufacture and maintain the positional accuracy at the same time. Design 5 has higher durability and accuracy, because we can easily to check the accuracy of the subsystem-level calibration targets and make each more durable.
Hence we choose D5.

6. Cyber Physical Architecture

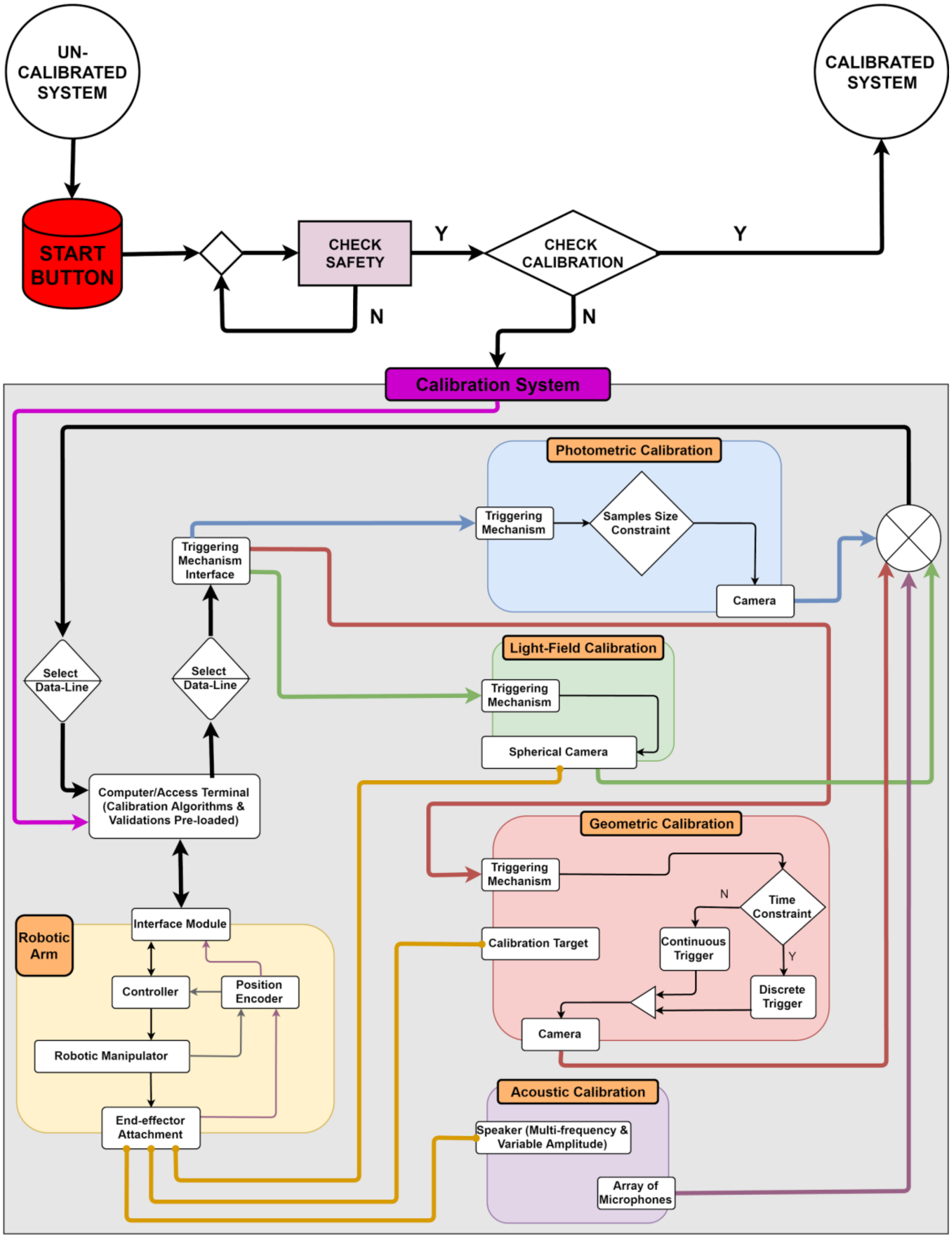


Figure 6.1 Cyber Physical Architecture

The interaction of the cyber physical components takes place as follows:

- Robotic Arm: The robotic arm is one of the major components to be used in this system. The robotic arm would have a controller and would be equipped with position sensors which would send the position of the end effector to the access terminal / computer. The robotic arm would also have end effector attachments for all the four types of calibration of the capture system.

- Calibration Target: This target would be used for the geometric calibration. The motion of this target would be controlled by the robotic arm, which would send the position of the target back to the computer to trigger the cameras to capture images.

- Spherical Camera: A spherical camera would be used to compute the illumination of the entire capture system. This camera needs to be calibrated first and then used to capture images which would help in calculating the illumination of the capture system.

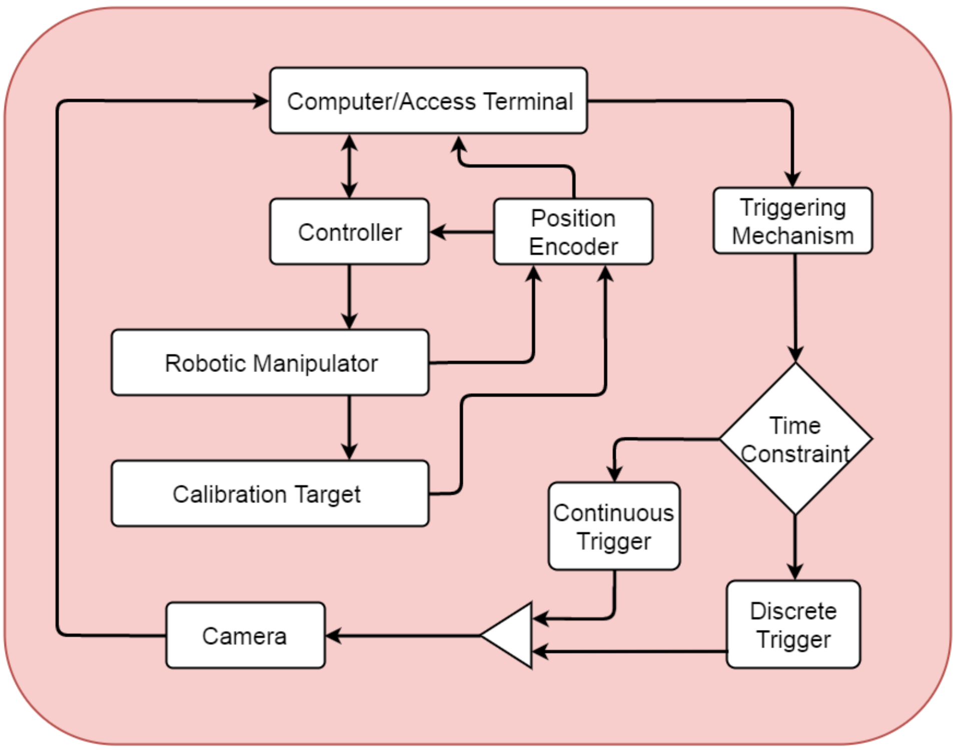
- A speaker would emit multi frequency and variable amplitude signals, which would be received by a 3 -directional differential and pressure microphone. The difference from these two signals would be used to calibrate the microphones.

- All the signals would be received by the access terminal which would compute the calibration parameters for the various components of the system.

7. Subsystem Description

The system is divided into four different subsystems according to the functional architecture: geometric calibration system, photometric calibration system, light field calibration system and acoustic calibration system. Generally speaking, when we push the start button, the whole system will begin by checking the safety situation and present accuracy, if the system needs calibration, we will carry out the four steps of calibration procedure successively.

7.1 Geometric calibration subsystem



7.1 Geometric calibration subsystem

The task of geometric calibration can be divided into 3 parts: the manipulation and control part, the image capturing part and the data processing and calibration part.

7.1.1 Manipulation and control

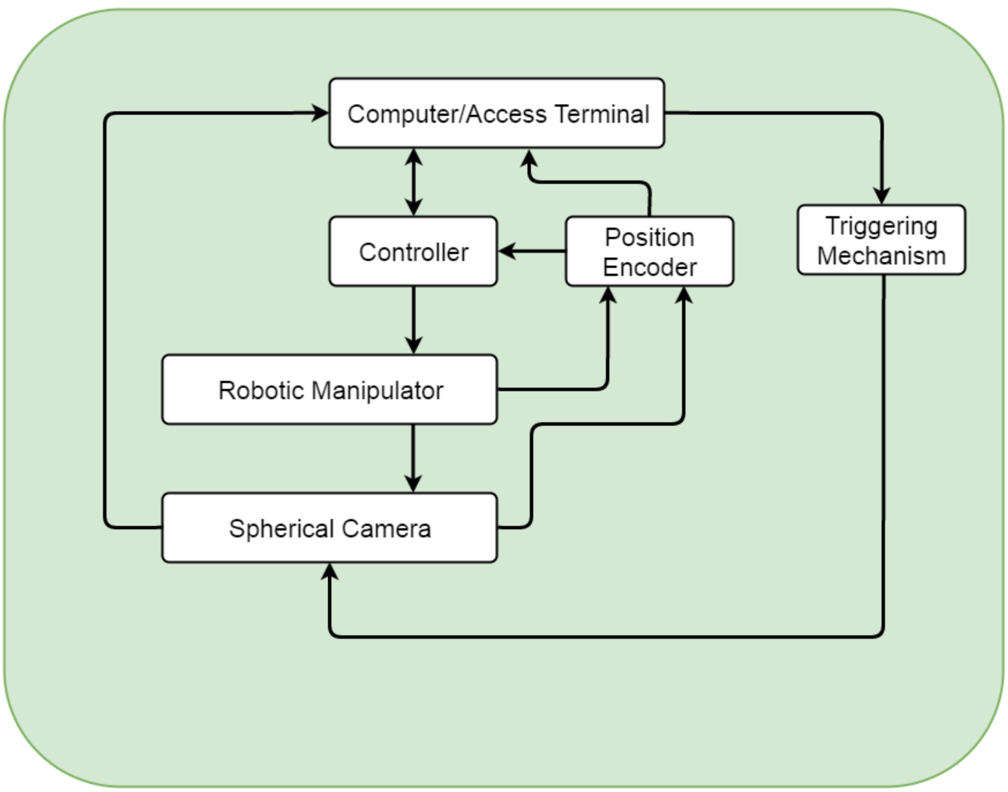
From the access terminal, we give instructions to control the ABB Robotic Arm which has the calibration target and sensors on it. The ABB robotic arm will then move the calibration target in a certain pattern according to the motion planning algorithm, and the sensors on it will collect position data. The system will send back the encoded positional data back to the computer and used for the following calibration procedure.

7.1.2 Image capturing

Also from the access terminal, we give instructions to the triggering mechanism. Under that mechanism, the 12 MP @ 73 fps canon cameras will be triggered to capture images. And there are two ways of image capturing, one is the continuous way and then other is the discrete way, depending on whether there is time constraint. For continuous trigger, the ABB robotic arm will move continuously with no pause, and the cameras will be triggered to capture images of the calibration target during the process. This will be quick, but we need to consider the motion blur and might need some steps of post-processing for the images we take. For discrete trigger, the ABB robotic arm will move in a discrete pattern with pause, and the cameras will be triggered to capture images during the pause. Then this will be comparatively slower, but we will be able to get accurate images for calibration process. When finishing capturing, all the images will be sent back to the computer and used for the following calibration procedure.

7.1.3 Data processing and calibration

During this part, we will use the captured image data and the position data of the calibration target to do the calibration calculation. We will call the geometric calibration algorithm to do the calibration work for multi cameras, and then the parameters of cameras and the positional and rotational data will be stored in a certain unit.



7.2 Light field calibration subsystem

7.2 Light Field calibration subsystem

The task of light-field calibration can be divided into 3 parts: the manipulation and control part, the sensing part and the data processing and calibration part.

7.2.1 Manipulation and control

From the access terminal, we give instructions to control the ABB Robotic Arm which has the spherical cameras and sensors on it. The ABB robotic arm will then move the spherical camera in a certain pattern according to the motion planning algorithm, doing calibration for the spherical camera and then collect illumination and position data. The system will send back the encoded data back to the computer and used for the following calibration procedure.

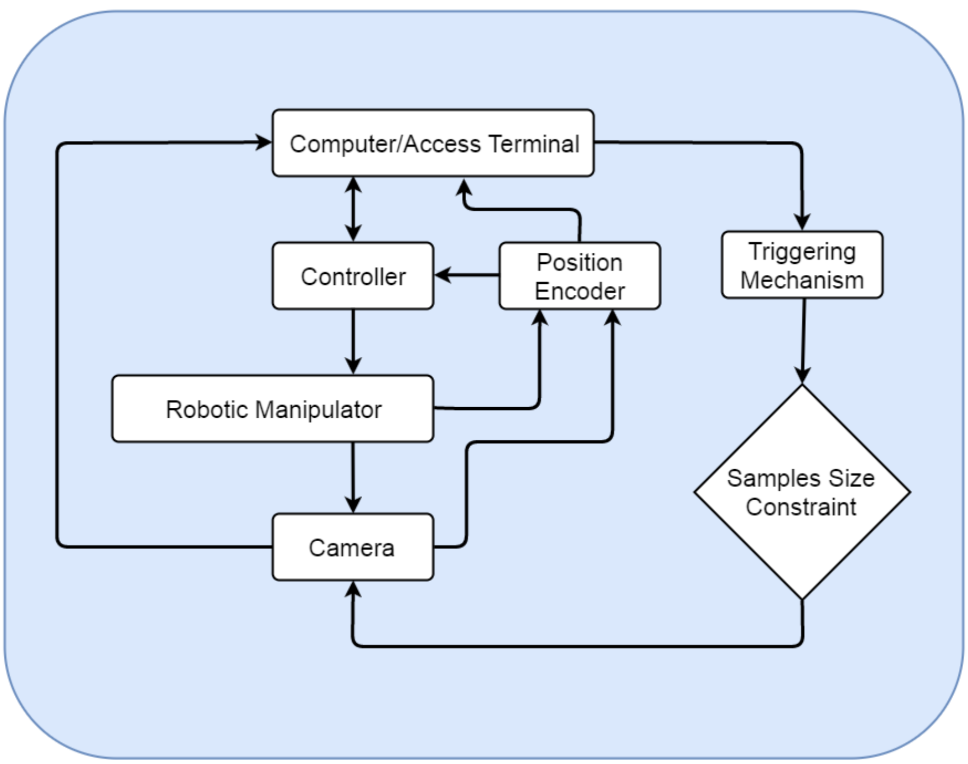
7.2.2 Sensing

Also from the access terminal, we give instructions to the triggering mechanism. Under that mechanism, the spherical cameras will be triggered to capture images and then sense the illumination data at a specific position. When finishing sensing and data collecting, all the illumination and the accordingly position data will be sent back to the computer.

7.2.3 Data processing and calibration

During this part, we will use the captured images and encoded position data to calibrate the single spherical camera, the process is the same as geometric calibration. After that, the illumination data at a certain position sensed by the spherical camera will be stored in a certain unit.

7.3 Photometric calibration subsystem



7.3 Photometric calibration subsystem

The task of photometric calibration can be divided into 3 parts: the manipulation and control part, the image capturing part and the data processing and calibration part.

7.3.1 Manipulation and control

From the access terminal, we give instructions to control the ABB Robotic Arm which has the calibration target on it. The ABB robotic arm will then move the calibration target in a certain pattern according to the motion planning algorithm, and the sensors on it will collect the photon data. The system will send back the encoded data back to the computer and used for the following calibration procedure.

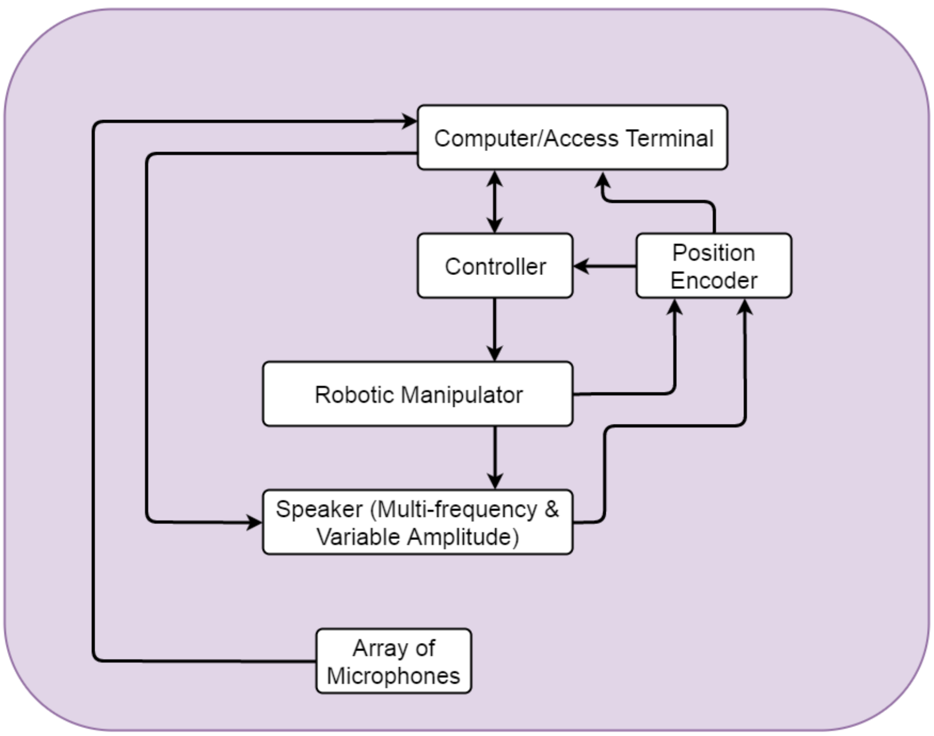
7.3.2 Image capturing

Also from the access terminal, we give instructions to the triggering mechanism. Under that mechanism, and refer to a constraint on sample size, the cameras will be triggered to capture images with different levels of light field. When finishing capturing, all the images and photon data will be sent back to the computer and used for the following calibration procedure.

7.3.3 Data processing and calibration

During this part, we will use the captured image data and the photon data of a certain image capture to do the calibration calculation. We will call the photometric calibration algorithm to do the calibration work for multi cameras, and then the parameters of cameras and the offset modification will be stored in a certain unit.

7.4 Acoustic calibration subsystem



7.4 Acoustic calibration subsystem

The task of acoustic calibration can be divided into 3 parts: the manipulation and control part, the sound signals emitting part and the data processing and calibration part.

7.4.1 Manipulation and control

From the access terminal, we give instructions to control the ABB Robotic Arm which has the speaker on it. The ABB robotic arm will then move the speaker in a certain pattern according to the motion planning algorithm, and the speaker will continuously send out signals with multi-frequency and variable amplitude. The system will send back the encoded position data back to the computer and used for the following calibration procedure.

7.4.2 Sound signal emission

We need to design a circuit which can let the speaker continuously send out sound signals with multi-frequency and variable amplitude as we wish.

7.4.3 Data processing and calibration

During this part, we will use the array of microphones to collect sound signals and store the time when it receives the signal and the amplitude of signals in the computer. Along with the encoded position data of the speaker, we will be able to do the calibration calculation. We will then design a specific algorithm for acoustic calibration for multi microphones, and then the parameters of microphones will be stored in a certain unit.

8.Project Management

8.1 Tasks

The following milestones and tasks have been set for the project. A validation test has also been added for each milestone.

Table 8.1: FALL SEMESTER TASK ASSIGNMENT

Millstone	**Output**	**Tasks**	**Validation test**
		Fall	
1.Setting up prototype	1.1 Prototype O1.2 Control System for Robotic Arm	T1.1 Configuring the AEROTECH arm T1.2 Camera interface setting T1.2 Designing calibration target T1.3 Designing Computer interface	V1.1 Prototype performance test
2.Execution-geometry	2.1 Geometry calibration system on prototype O2.2 Control Strartegy	T2.1 Image pre-processing T2.2 Motion planning T2.3 Execute geometry algorithm	V2.1 Geometric subsystem test

		T2.4 Subsystem test & validation	
3.Execution-light field	3.1 Light field calibration system on prototype O3.2. Control program	T3.1 Calibrate the spherical camera T3.2 Data collection T3.3 Test & Validation the subsystem	V3.1 Light field subsystem test
4.ABB robotic arm setting	4.1 ABB control algorithm	T4.1 Technical file & Training T4.2 Basic setting & control	V4.1 ABB control test
	Spring		
5.Execution-Photometry	5.1 Photometric calibration system on prototype 5.2 Control program	T5.1 Image pre-processing T5.2 Motion planning T5.3 Execute photometry algorithm T5.4 Subsystem test & validation	V5.1 Photometric subsystem test
6.Execution-Acoustic field	6.1 Acoustic calibration system on prototype 6.2 Control program	T6.1 Develop basic acoustic calibration algorithm T6.2 Motion planning T6.3 Improve the algorithm with machine learning T6.4 Circuit design T6.5 Subsystem test & validation	V6.1 Acoustic field subsystem test
7.System integration	7.1 Calibration system 7.2 Control program	T7.1 Calibration target T7.2 Integration T7.3 System test & validation 1 T7.4 Trouble shooting & improvement T7.5 System test & validation 2	V7.1 integration test 1 V7.2 integration test 2

8.2 Schedule of Tasks

Table 8.2: GANTT CHART

Excalibr																																		
Task	People	SEP	OCT					NOV				DEC				JAN					FEB				MAR				APR				MAY	
	Date:	9/26	10/3	10/10	10/17	10/24	10/31	11/7	11/14	11/21	11/28	12/5	12/12	12/19	12/26	1/2	1/9	1/16	1/23	1/30	2/6	2/13	2/20	2/27	3/6	3/13	3/20	3/27	4/3	4/10	4/17	4/24	5/1	5/8
1.0 Setting up prototype																																		
1.1 AEROTECH arm setting	B&P																																	
1.2 Camera interface setting	S&M&C																																	
1.2 Build Calibration target	P																																	
1.3 Computer interface	M&C																																	
2.0 Execution-geometry																																		
2.1 Image pre-processing	C																																	
2.2 Motion planning	S&P&B																																	
2.3 Execute geometric algorithm	M&C																																	
2.4 Subsystem test & validation	P																																	
3.0 Execution-light field																																		
3.1 Calibrate the spherical camera	C&M																																	
3.2 Data collection	B&S																																	
3.3 Test & Validation the subsystem	P&B																																	
4.0 ABB robot arm setting																																		
4.1 Technical Training	P&S&B																																	
4.2 Basic setting & control	P&S&B																																	
A.0 Buff Time in Fall																																		
A.1 Buff Time	C&M&S&B&P																																	
Spring Break	ALL																																	
5.0 Execution-Photometry																																		
5.1 Image pre-processing	C																																	
5.2 Motion planning	S&P&B																																	
5.3 Execute photometry algorithm	M&C																																	
5.4 Subsystem test & validation	P																																	
6.0 Execution-Acoustic field																																		
6.1 Develop basic acoustic calibration algorithm	C&M&S&B&P																																	
6.2 Motion planning	S&P&B																																	
6.3 Improve the algorithm with machine learning	M&C																																	
6.4 Circuit design	B																																	
6.5 Subsystem test & validation	P																																	
7.0 System integration																																		
7.1 Calibration target	C&M&S&B&P																																	
7.2 Integration	S&P&B																																	
7.3 System test & validation	M&C																																	
7.4 Trouble shooting & improvement	B																																	
7.5 Final System Test & Validation 2	P&B																																	
B.0 Buff Time																																		
B.1 Buff Time	C&M&S&B&P																																	

8.3 System validation plan

Table 8.2.1 Fall validation plan

Test ID	V1.1	
Test Name	Prototype test	
Test description	To test prototype system	
Place	Oculus research	
Test necessary	Camera, Robot arm(AEROTECH), calibration target, control system	
Steps	Description	Successful Criteria
1	Move robot arm	Can move in X Y Z direction
2	Trigger the camera	When arm moved to specific position, trigger the camera
3	Capture Image	Capture Images and Store them.

Table 8.2.2 Fall validation plan

Test ID	V2.1	
Test Name	Geometry subsystem test	
Test description	To test geometric calibration system	
Place	Oculus research	
Test necessary	Camera, robot arm(AEROTECH), calibration target, control system	
Steps	Description	Successful Criteria
1	Move robot arm	Follow the motion planning algorithm.
2	Trigger the camera	When moved to a specific position, trigger the camera.
3	Capture Image	Capture Image and Store it successfully.
4	Apply calibration algorithm	Cater to a 100 micrometer level of positional accuracy

Table 8.2.3 Fall validation plan

Test ID	V3.1	
Test Name	Light field subsystem test	
Test description	To test light field calibration system	
Place	Oculus research	
Test necessary	Camera, robot arm(AEROTECH), calibration target, control system	
Steps	Description	Successful Criteria
1	Move robot arm	Follow the motion planning algorithm.
2	Trigger the camera	When moved to a specific position, trigger the camera.
3	Take picture	Capture Image and Store it successfully.
4	Apply calibration algorithm	Successfully use algorithm

Table 8.2.4 Fall validation plan

Test ID	V4.1	
Test Name	ABB control test	
Test description	To test ABB control system	
Place	Oculus research	
Test necessary	robot arm (ABB robot arm), , control system	
Steps	Description	Successful Criteria
1	Move robot arm	Follow the motion planning algorithm.
2	Check the interface with the calibration target	Can connect with calibration target
3	Check the interface with the geometry calibration algorithm	Can work with geometric calibration algorithm

4	Check the interface with the light field calibration algorithm	Can work with light field calibration algorithm

Table 8.3.1 Spring Validation Plan

Test ID	V5.1	
Test Name	Photometry subsystem test	
Test description	To test Photometry subsystem	
Place	Oculus research	
Test necessary	Camera, robot arm(AEROTECH), calibration target, control system	
Steps	Description	Successful Criteria
1	Move robot arm	Follow the motion planning algorithm.
2	Trigger the camera	When moved to a specific position, trigger the camera.
3	Take picture	Capture Image and Store it successfully.
4	Apply calibration algorithm	Successfully use algorithm

Table 8.3.2 Spring Validation Plan

Test ID	V6.1	
Test Name	Acoustic field test	
Test description	To test Acoustic field subsystem	
Place	Oculus research	
Test necessary	Camera, robot arm(AEROTECH), calibration target, control system, speaker	
Steps	Description	Successful Criteria
1	Move robot arm	Move like the move planning
2	Trigger the speaker	When move to specific position, trigger the speaker

3	Recode the position	Check the position data
4	Apply calibration algorithm	Successfully use algorithm

Table 8.3.3 Spring Validation Plan

Test ID	V7.1	
Test Name	integrated test 1	
Test description	To test whole system	
Place	Oculus research	
Test necessary	Camera, robot arm (ABB robot arm), calibration target, control system, speaker	
Steps	Description	Successful Criteria
1	Use geometry algorithm	Minimalistic error overall
2	Use light field algorithm	Minimalistic error overall
3	Use photometry algorithm	Minimalistic error overall
4	Use acoustic field algorithm	Minimalistic error overall

Table 8.3.4 Spring Validation Plan

Test ID	V7.2	
Test Name	ABB control test	
Test description	To test ABB control system	
Place	Oculus research	
Test necessary	Camera, robot arm (ABB robot arm), calibration target, control system, speaker	
Steps	Description	Successful Criteria
1	Use geometry algorithm	Accurate upto 100 micrometers

2	Use light field algorithm	Minimalistic error overall
3	Use photometry algorithm	Minimalistic error overall
4	Use acoustic field algorithm	Accurate upto 100 micrometers

8.4 Responsibilities

Table 8.4.1 Distribution of responsibilities

	Responsibility of group members		
	Subsystem	**Group Member**	
	Robot Arm Control	Sam & Peter & Mandy	
	Image Capturing	Sid & Mandy & Cece	
	Calibration Algorithm	Mandy & Cece & Sid	
	User Interface	Cece & Mandy & Sam	
	Calibration Target	Peter & Sam	

8.5 Risk management

Table 8.5.1 Potential risks in project

Major category	Potential risk	Possible approach
1.Human factor	1.Lethargy. 2.Not sufficient knowledge. 3.Tedious.	1.Set check point for each task 2.Ask Oculus employees and experienced students for guidance 3.Implement Fines to penalize irresponsible behaviors.
2.Robot Arm	1.Complete System failure. 2.Collateral damage to humans and instruments. 3.Faulty positional feedback.	1.Use the robot arm in prototype stage as an alternative. 2. Contact with company technician to implement safety protocols during operation. 3.Use software based error correction algorithms.
3.Camera	1.System failure. 2.Control problem.	1.Build a small scale system to observe fallout from such failures and develop corrective procedures.

4.Calibration target	1.Manufacture delay. 2.Manufacturing defects.	1.Design and Manufacture the calibration target in the beginning. 2. Use the 3D measurement data rather than design data to calibrate.
5.System	1.Integration problem 2.Overshoot time constraint.	1.Study the relationship of the different calibration processes and design the framework in ROS (develop custom libraries in C++ & Python). Build and test the small-scale system. 2. Estimate the duration and latency in each process and try to reduce the overall operation time.

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Book: Computer Vision: Algorithms and Applications-- Richard Szeliski