"Error Characterization

of

OptiTrack Motion *Capture* System"

...an Investigative Report

Submitted by

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II Objectives

The primary focus of this study was to characterize the error produced in measurement of position of an object with respect to the calibrated origin by the *OptiTrack* Motion Capture System, presently installed at the Digital Control Laboratory, Department of Electrical Engineering, IIT Delhi and hence derive bounds for it. An “object” here could be anything from a static rigid/point body to a randomly moving rigid/point body.

Aside from that, the various factors affecting the accuracy of the system had to be explored and their respective contributions to the overall error had to be characterized and analyzed.

On the basis of these results we had to figure out ways to curb the overall positional error due to the system and suggest an optimum set-up for the system to be installed at a new facility for carrying out accurate experiments related to testing of Control Algorithms on UAVs/Quadrotors.

The following is a Broad classification of the objectives undertaken for this study :

- → Developing an Understanding of operation and nuances of the *OptiTrack* Motion Capture System
- → Narrowing-in upon the factors that could possibly affect the error produced by the system
- → Carrying out Investigative experiments to compare the obtained readings with respect to the ground truth under different operating conditions to assess the error obtained and the effect of various factors
- → Analysis of obtained data to draw conclusive inferences
- → Check for repeatability and consistency of the system
- → Collating all the inferences to propose an optimum setup for the new installation and predict the bounds of error that may exist

III Introduction

The currently installed Motion Capture System includes 8 *OptiTrack Flex-13*[1] Infrared Cameras, 6 of which are connected to a single *Optihub*[2] and the remaining 2 to the other. These *Optihubs* are further individually connected via USB to the Central computing system that runs Motive 1.10[3] which is OptiTrack's official Motion Capture System and performs real-time multi-spectral data fusion to determine the position of the object under consideration, tracked using reflective markers[4] .

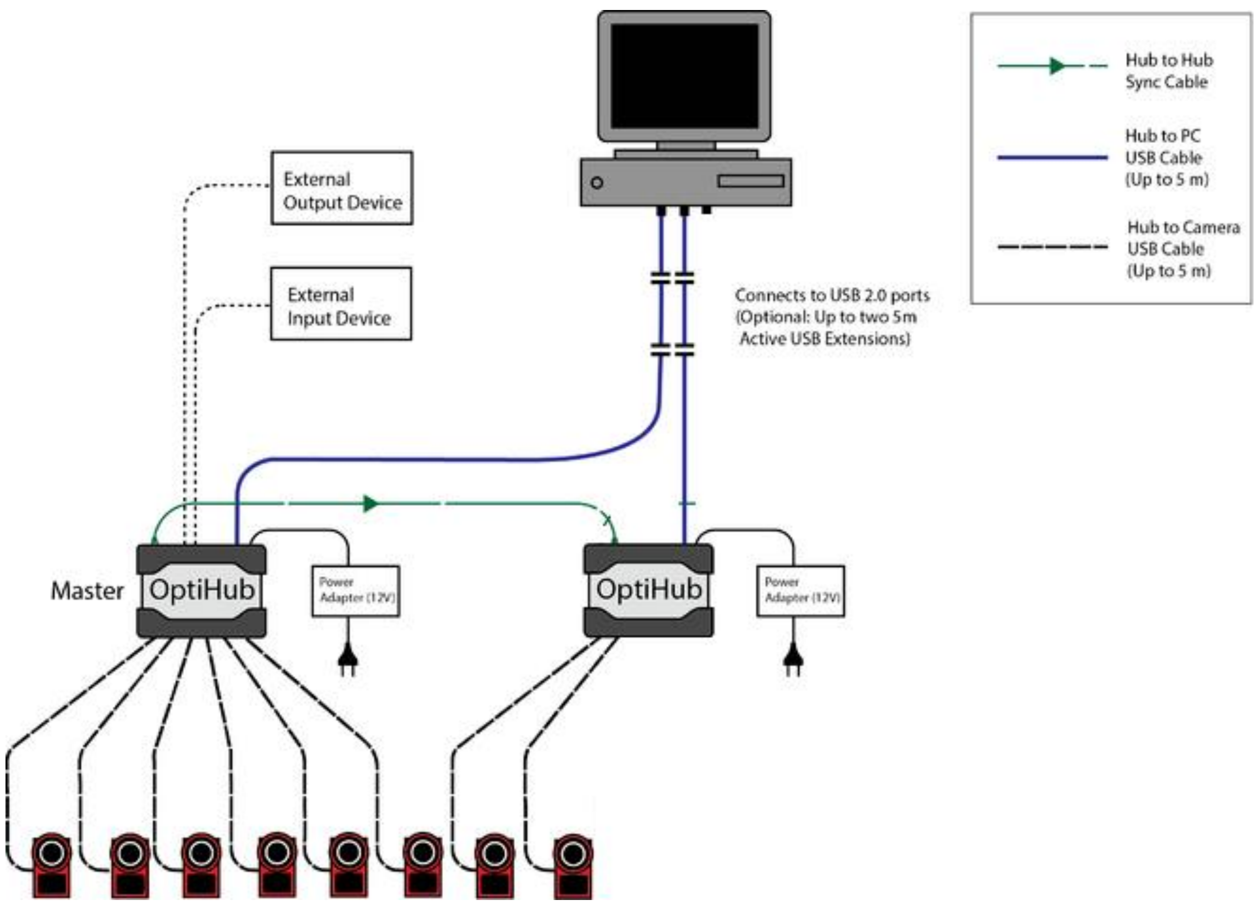

Fig 1. SCHEMATIC DEPICTING THE CONNECTIONS FOR THE CURRENT MOTION CAPTURE SYSTEM SET-UP

Fig. 2A

Fig. 2B

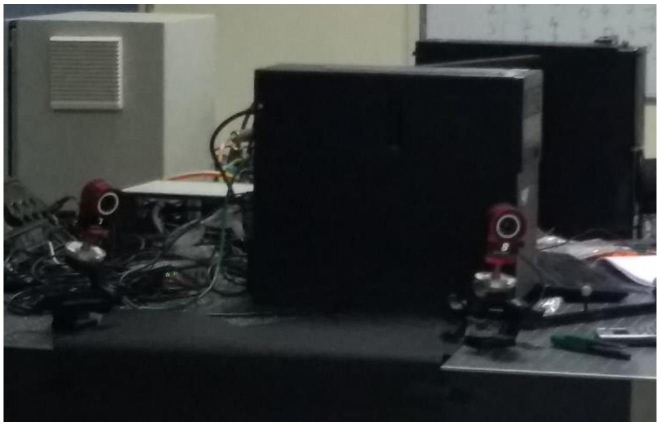

Fig. 2C

Fig. 2 A,B & C Current Set-up at the Digital Control Laboratory

Based on the discussions with students who had worked with the system previously and by analyzing the operations and set-up instructions given in the

Optitrack quick start guide[5] we figured out the following parameters to be critically important towards the accuracy of the system :

- → Reflectivity of the capture surface
- → Light(Radiation) intensity in the capture Volume
- → Distance from the calibrated origin
- → Presence of multiple markers or the amount of masking overlay in the live images/data obtained.

All further experiments to characterize the system's error were designed, keeping the above parameters in mind.

Also upon careful examination of the facts mentioned in [5] it became evident that the current set-up as shown in Fig. 2 A,B,&C is not an optimal utilization of the equipment thus the results regarding the error obtained in the system's observations may improve to some extent upon alteration of the camera arrangement as per instructions.

IV Experimentation Methodology

The following process was adopted for determination of error under all different set of conditions:

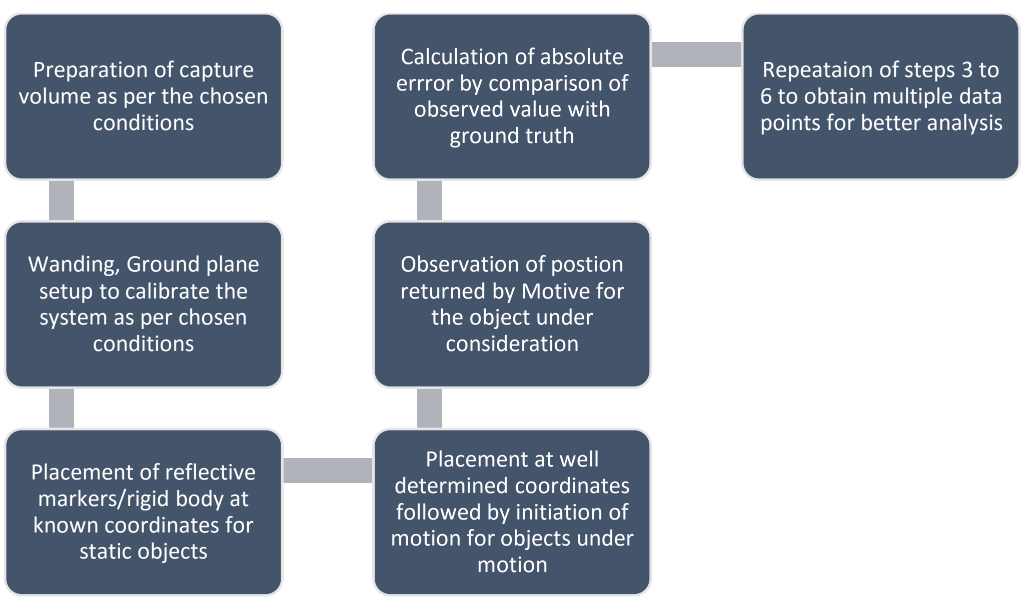

Fig. 3. The error determination Algorithm

The algorithm depicted by Figure 3 was executed for the following set of conditions :-

S. No.	**Type of Object**	**Nature of Capture surface**	**Amount of lighting in Capture volume**	**Dimensionality For error check**	**Type of motion**
1	Point Object	Reflective	High	1D	Static
2	Point Object	Reflective	Low	1D	Static
3	Point Object	Dark	High	1D	Static
4	Point Object	Dark	Low	1D	Static
5	Point Object	Reflective	High	2D	Static
6	Point Object	Reflective	Low	2D	Static
7	Point Object	Dark	High	2D	Static
8	Point Object	Dark	Low	2D	Static
9	Point Object	Reflective	High	3D	Static
10	Point Object	Reflective	Low	3D	Static
11	Point Object	Dark	High	3D	Static
12	Point Object	Dark	Low	3D	Static
13	Rigid Body	Reflective	High	1D	Static
14	Rigid Body	Reflective	Low	1D	Static
15	Rigid Body	Dark	High	1D	Static
16	Rigid Body	Dark	Low	1D	Static
17	Rigid Body	Reflective	High	2D	Static
18	Rigid Body	Reflective	Low	2D	Static

19	Rigid Body	Dark	High	2D	Static
20	Rigid Body	Dark	Low	2D	Static
21	Rigid Body	Dark	Low	3D	Static
22	Point Object	Dark	Low	3D	Moving

Table 1. Various Cases for Error Characterization

Apart from these, experiments were also carried out to test the repeatability of this system.

The following are glimpses of the experimental set-up for the cases mentioned in Table 1:

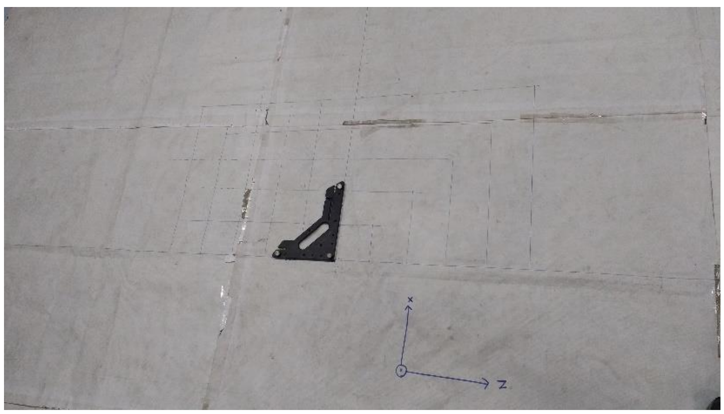

Fig 4. Setting of Ground plane using the *OptiTrack*-set Square

Fig. 5. Set-up for Point objects on a reflective Surface with Bright lighting in 2D

Fig. 6 Set-up for Point objects on a Dark surface with Bright lighting in 3D

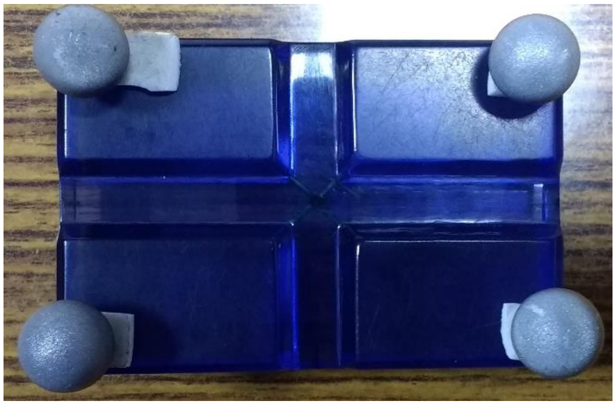

Fig. 7 The rigid body used for experimentation (It is ideal to have number of markers = Number of vertices of top face so as to avoid IR reflection amongst the markers and to ensure proper detection of the body)

Fig. 8 Set-up for a moving Point Object in 3D on a Dark Surface with dim lighting

 

Fig. 9 Effect of Dim V/s Bright lighting conditions on the capture volume

V Results Obtained

The following results were obtained for error obtained in all the cases mentioned in section IV. All dimensions (including that of absolute error) are in mm.

V.1.1 for a point object in 1D :

For 1 dimension(along Z) offset : 0.000633m						
S.no.	Surface	Environmental Light Intensity	Position Obtained inMotive(pos) (mm)	Actual Position (mm)	pos-offset	error (absolute)
1	Refelctive	High	0.633	0	0	0
2	Refelctive	High	98.199	100	97.566	2.434
3	Refelctive	High	197	200	196.367	3.633
4	Refelctive	High	296.183	300	295.55	4.45
5	Refelctive	High	394.043	400	393.41	6.59
6	Refelctive	High	491.816	500	491.183	8.817
7	Refelctive	High	592.01	600	591.377	8.623
8	Refelctive	High	689.732	700	689.099	10.901
9	Refelctive	High	786.86	800	786.227	13.773
10	Refelctive	High	886.547	900	885.914	14.086
11	Refelctive	High	985.857	1000	985.224	14.776

For 1 dimension (along Z)Offset:-.001573m						
S.no.	Surface	Environmental Light Intensity	Position Obtained inMotive(pos) (mm)	Actual Position (mm)	pos-offset	error (absolute)
1	Reflective	Low	-1.573	0	0	0
2	Reflective	Low	96.226	100	97.799	2.201
3	Reflective	Low	196.033	200	197.606	2.394
4	Reflective	Low	293.92	300	295.493	4.507
5	Reflective	Low	392.664	400	394.237	5.763
6	Reflective	Low	491.905	500	493.478	6.522
7	Reflective	Low	589.9	600	591.473	8.527
8	Reflective	Low	688.693	700	690.266	9.734
9	Reflective	Low	785.946	800	787.519	12.481
10	Reflective	Low	885.249	900	886.822	13.178
11	Reflective	Low	983.462	1000	985.035	14.965

		For 1 dimension (along Z)Offset:-.002014m				
S.no.	**Surface**	**Environmental Light Intensity**	**Position Obtained inMotive(pos) (mm)**	**Actual Position (mm)**	**pos-offset**	**error (absolute)**
1	Dark	High	2.014	0	0	
2	Dark	High	-299.102	-300	-301.116	1.116
3	Dark	High	-197.162	-200	-199.176	0.824
4	Dark	High	-97.875	-100	-99.889	0.111
5	Dark	High	101.625	100	99.611	0.389
6	Dark	High	202.089	200	200.075	0.075
7	Dark	High	302.728	300	300.714	0.714
8	Dark	High	400.877	400	398.863	1.137
9	Dark	High	501.657	500	499.643	0.357
10	Dark	High	600.697	600	598.683	1.317
11	Dark	High	700.049	700	698.035	1.965

		For 1 dimension (along Z)Offset:-.001572m				
S.no.	**Surface**	**Environmental Light Intensity**	**Position Obtained inMotive(pos) (mm)**	**Actual Position (mm)**	**pos-offset**	**error (absolute)**
1	Dark	Low	1.572	0	0	
2	Dark	Low	-299.473	-300	-301.045	1.045
3	Dark	Low	-198.11	-200	-199.682	0.318
4	Dark	Low	-99.328	-100	-100.9	0.9
5	Dark	Low	102.045	100	100.473	0.473
6	Dark	Low	202.052	200	200.48	0.48
7	Dark	Low	302.293	300	300.721	0.721
8	Dark	Low	401.715	400	400.143	0.143
9	Dark	Low	501.41	500	499.838	0.162
10	Dark	Low	601.161	600	599.589	0.411
11	Dark	Low	701.751	700	700.179	0.179

V.1.2 for a point object in 2D :

					Obtained Offset along X:.007001m Obtained offset along Z:-.001545m					
			Obtained position along X (mm) (Pos X)	Obtained position along Z(mm) (Pos Z)	Actual Position along X(mm)	Actual Position along Z(mm)	Pos X-offset(mm)	Pos Z-offset(mm)	error (x) (absolute)(mm)	error(z)(absolute) (mm)
1	Dark	High	7.001	-1.545	0	0	0	0	0	0
2	Dark	High	101.491	100.541	100	100	94.49	102.086	5.51	2.086
3	Dark	High	200.562	200.398	200	200	193.561	201.943	6.439	1.943
4	Dark	High	299.668	300.047	300	300	292.667	301.592	7.333	1.592
5	Dark	High	399.147	397.198	400	400	392.146	398.743	7.854	1.257
6	Dark	High	489.094	510.378	500	500	482.093	511.923	17.907	11.923
7	Dark	High	-94.643	94.432	-100	100	-101.644	95.977	1.644	4.023
8	Dark	High	-194.946	197.967	-200	200	-201.947	199.512	1.947	0.488
9	Dark	High	-290.629	300.048	-300	300	-297.63	301.593	2.37	1.593
10	Dark	High	-389.031	398.362	-400	400	-396.032	399.907	3.968	0.093
11	Dark	High	-500.139	483.696	-500	500	-507.14	485.241	7.14	14.759

					Obtained Offset along X:.007446m Obtained offset along Z:-.001214m					
			Obtained position along X (mm) (Pos X)	Obtained position along Z(mm) (Pos Z)	Actual Position along X(mm)	Actual Position along Z(mm)	Pos X-offset(mm)	Pos Z-offset(mm)	error (x) (absolute)(mm)	error(z)(absolute) (mm)
1	Dark	Low	7.466	-1.214	0	0	0	0	0	0
2	Dark	Low	102.927	102.028	100	100	95.461	103.242	4.539	3.242
3	Dark	Low	200.521	200.674	200	200	193.055	201.888	6.945	1.888
4	Dark	Low	298.37	300.983	300	300	290.904	302.197	9.096	2.197
5	Dark	Low	398.79	398.899	400	400	391.324	400.113	8.676	0.113
6	Dark	Low	487.589	511.263	500	500	480.123	512.477	19.877	12.477
7	Dark	Low	-94.289	96.14	-100	100	-101.755	97.354	1.755	2.646
8	Dark	Low	-196.054	196.564	-200	200	-203.52	197.778	3.52	2.222
9	Dark	Low	-291.179	299.837	-300	300	-298.645	301.051	1.355	1.051
10	Dark	Low	-388.771	396.678	-400	400	-396.237	397.892	3.763	2.108
11	Dark	Low	-500.861	483.487	-500	500	-508.327	484.701	8.327	15.299

Obtained Offset along X:.003640m Obtained offset along Z:-.002393m										
			Obtained position along X (mm) (Pos X)	Obtained position along Z(mm) (Pos Z)	Actual Position along X(mm)	Actual Position along Z(mm)	Pos X-offset(mm)	Pos Z - offset(mm)	error (x) (absolute)(mm)	error(z)(absolute) (mm)
1	Refelctive	High	3.64	2.393	0	0	0	0	0	0
2	Refelctive	High	104.363	100.447	100	100	100.723	98.054	0.723	1.946
3	Refelctive	High	204.219	200.8	200	200	200.579	198.407	0.579	1.593
4	Refelctive	High	308.669	298.203	300	300	305.029	295.81	5.029	4.19
5	Refelctive	High	410.661	386.478	400	400	407.021	384.085	7.021	15.915
6	Refelctive	High	509.235	484.445	500	500	505.595	482.052	5.595	17.948
7	Refelctive	High	-94.853	100.797	-100	100	-98.493	98.404	1.507	1.596
8	Refelctive	High	-194.865	199.198	-200	200	-198.505	196.805	1.495	3.195
9	Refelctive	High	-293.925	301.822	-300	300	-297.565	299.429	2.435	0.571
10	Refelctive	High	-387.424	407.061	-400	400	-391.064	404.668	8.936	4.668
11	Refelctive	High	-493.356	513.032	-500	500	-496.996	510.639	3.004	10.639

			Obtained position along X (mm) (Pos X)	Obtained position along Z(mm) (Pos Z)	Actual Position along X(mm)	Actual Position along Z(mm)	Pos X-offset(mm)	Pos Z - offset(mm)	error (x) (absolute)(mm)	error(z)(absolute) (mm)
1	Reflective	Low	1.818	1.184	0	0	0	0	0	0
2	Reflective	Low	103.577	101.897	100	100	101.759	100.713	1.759	0.713
3	Reflective	Low	203.219	201.85	200	200	201.401	200.666	1.401	0.666
4	Reflective	Low	306.635	298.51	300	300	304.817	297.326	4.817	2.674
5	Reflective	Low	409.433	386.93	400	400	407.615	385.746	7.615	14.254
6	Reflective	Low	508.759	486.78	500	500	506.941	485.596	6.941	14.404
7	Reflective	Low	-97.408	100.887	-100	100	-99.226	99.703	0.774	0.297
8	Reflective	Low	-197.18	198.468	-200	200	-198.998	197.284	1.002	2.716
9	Reflective	Low	-296.555	300.309	-300	300	-298.373	299.125	1.627	0.875
10	Reflective	Low	-390.943	404.913	-400	400	-392.761	403.729	7.239	3.729
11	Reflective	Low	-497.262	510.524	-500	500	-499.08	509.34	0.92	9.34

V.1.3. for a point object in 3D:

For Reflective surface with dim lighting														
Offset along x(mm):-		1.818			Correction along X(mm) :		38.5							
Offset along y(mm):-		0.997												
Offset along z(mm):-		1.184												
Actual position(mm)			Corrected Actual Position (mm)			Observed Position(pos)			Pos-offset			Absolute error		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
-500	132	500	-461.5	132	500	-453.114	138.753	506.778	-454.932	137.756	505.594	6.568	5.756	5.594
-500	297	500	-461.5	297	500	-452.17	301.086	504.923	-453.988	300.089	503.739	7.512	3.089	3.739
-500	384	500	-461.5	384	500	-451.661	389.144	504.399	-453.479	388.147	503.215	8.021	4.147	3.215
-500	527.35	500	-461.5	527.35	500	-450.67	531.893	505.075	-452.488	530.896	503.891	9.012	3.546	3.891
100	132	100	138.5	132	100	142.021	132.369	100.319	140.203	131.372	99.135	1.703	0.628	0.865
100	297	100	138.5	297	100	142.406	294.541	98.64	140.588	293.544	97.456	2.088	3.456	2.544
100	384	100	138.5	384	100	142.612	382.66	98.138	140.794	381.663	96.954	2.294	2.337	3.046
100	527.35	100	138.5	527.35	100	143.76	525.116	97.219	141.942	524.119	96.035	3.442	3.231	3.965
200	132	200	238.5	132	200	242.444	132.438	204.365	240.626	131.441	203.181	2.126	0.559	3.181
200	297	200	238.5	297	200	243.236	294.595	203.031	241.418	293.598	201.847	2.918	3.402	1.847

For Reflective surface with bright lighting

Offset along x(mm):- 1.399

Offset along y(mm):- 0.801

Offset along z(mm):- 2.068

Correction along X(mm) : 38.5

Actual position(mm)			Corrected Actual Position (mm)			Observed Position(pos)			Pos-offset			Absolute error		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
500	132	500	538.5	132	500	538.942	135.368	482.942	537.543	134.567	480.874	0.957	2.567	19.126
500	297	500	538.5	297	500	539.173	297.714	480.577	537.774	296.913	478.509	0.726	0.087	21.491
500	384	500	538.5	384	500	539.596	385.7	479.94	538.197	384.899	477.872	0.303	0.899	22.128
500	527.35	500	538.5	527.35	500	540.994	480.011	480.011	539.595	479.21	477.943	1.095	48.14	22.057
-100	132	100	-61.5	132	100	-55.681	131.954	99.697	-57.08	131.153	97.629	4.42	0.847	2.371
-100	297	100	-61.5	297	100	-53.931	294.346	97.612	-55.33	293.545	95.544	6.17	3.455	4.456
-100	384	100	-61.5	384	100	-52.739	382.287	97.115	-54.138	381.486	95.047	7.362	2.514	4.953
-100	527.35	100	-61.5	527.35	100	-90.28	524.873	94.053	-91.679	524.072	91.985	30.179	3.278	8.015
-200	132	200	-161.5	132	200	-155.43	133.941	193.429	-156.829	133.14	191.361	4.671	1.14	8.639
-200	297	200	-161.5	297	200	-154.911	296.283	191.525	-156.31	295.482	189.457	5.19	1.518	10.543

For Dark surface with bright lighting

Offset along x(mm):- 0.214

Offset along y(mm):- 1.081

Offset along z(mm):- -0.965

Correction along X(mm) : 38.5

Actual position(mm)			Corrected Actual Position (mm)			Observed Position(pos)			Pos-offset			Absolute error		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
500	132	500	538.5	132	500	538.942	135.368	482.942	538.728	134.287	483.907	0.228	2.287	16.093
500	297	500	538.5	297	500	539.173	297.714	480.577	538.959	296.633	481.542	0.459	0.367	18.458
500	384	500	538.5	384	500	539.596	385.7	479.94	539.382	384.619	480.905	0.882	0.619	19.095
500	510	500	538.5	510	500	540.994	480.011	480.011	540.78	478.93	480.976	2.28	31.07	19.024
400	132	400	438.5	132	400	445.657	131.954	391.67	445.443	130.873	392.635	6.943	1.127	7.365
400	297	400	438.5	297	400	446.511	294.346	395.294	446.297	293.265	396.259	7.797	3.735	3.741
400	384	400	438.5	384	400	447.257	382.287	398.014	447.043	381.206	398.979	8.543	2.794	1.021
-400	510	400	-361.5	510	400	-344.807	511.412	400.564	-345.021	510.331	401.529	16.479	0.331	1.529
-400	132	400	-361.5	132	400	-344.151	136.42	408.244	-344.365	135.339	409.209	17.135	3.339	9.209
-400	297	400	-361.5	297	400	-344.589	298.651	404.455	-344.803	297.57	405.42	16.697	0.57	5.42

For Dark surface with dim lighting

Offset along x(mm):- 0.212

Offset along y(mm):- 2.019

Offset along z(mm):- 0.344

Correction along X(mm) : 38.5

Actual position(mm)			Corrected Actual Position (mm)			Observed Position(pos)			Pos-offset			Absolute error		
X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
200	132	200	238.5	132	200	237.785	134.89	195.812	237.573	132.871	195.468	0.927	0.871	4.532
200	297	200	238.5	297	200	236.437	297.102	193.272	236.225	295.083	192.928	2.275	1.917	7.072
200	384	200	238.5	384	200	236.025	385.024	192.636	235.813	383.005	192.292	2.687	0.995	7.708
200	510	200	238.5	510	200	235.427	509.86	191.988	235.215	507.841	191.644	3.285	2.159	8.356
300	132	300	338.5	132	300	342.769	135.261	290.74	342.557	133.242	290.396	4.057	1.242	9.604
300	297	300	338.5	297	300	342.818	297.499	289.225	342.606	295.48	288.881	4.106	1.52	11.119
300	384	300	338.5	384	300	343.051	385.603	288.627	342.839	383.584	288.283	4.339	0.416	11.717
300	510	300	338.5	510	300	343.528	510.337	288.318	343.316	508.318	287.974	4.816	1.682	12.026
-200	132	200	-161.5	132	200	-155.045	135.51	202.746	-155.257	133.491	202.402	6.243	1.491	2.402
-200	297	200	-161.5	297	200	-154.174	297.672	200.923	-154.386	295.653	200.579	7.114	1.347	0.579

V.2.1 for a rigid body in 1D:

Surface=dark,light=High				
Actual Z	observed Z	Offset:-	pos-off	abs error
-400	-400.78	0.54	-401.32	1.32
-300	-300.1	0.54	-300.64	0.64
-200	-199.86	0.54	-200.4	0.4
-100	-100.14	0.54	-100.68	0.68
0	0	0	0	0
100	100.36	0.54	99.82	0.18
200	200.98	0.54	200.44	0.44
300	300.67	0.54	300.13	0.13
400	401.04	0.54	400.5	0.5
500	500.83	0.54	500.29	0.29
600	600.09	0.54	599.55	0.45

Surface=dark,light=low				
Actual Z	observed	Offset:-	pos-off	abs error
-400	-400.78	-0.29	-400.49	0.49
-300	-300.1	-0.29	-299.81	0.19
-200	-199.86	-0.29	-199.57	0.43
-100	-100.14	-0.29	-99.85	0.15
0	0	-0.29	0.29	0.29
100	100.36	-0.29	100.65	0.65
200	200.98	-0.29	201.27	1.27
300	300.67	-0.29	300.96	0.96
400	401.04	-0.29	401.33	1.33
500	500.83	-0.29	501.12	1.12
600	600.01	-0.29	600.3	0.3

Surface=reflective,light=High				
Actual Z	observed Z	Offset:-	pos-off	abs error
0	0	0	0	0
100	95.5	-0.29	95.79	4.21
200	194.68	-0.29	194.97	5.03
300	293.44	-0.29	293.73	6.27
400	393.28	-0.29	393.57	6.43
500	492.6	-0.29	492.89	7.11
600	591.25	-0.29	591.54	8.46
700	690.82	-0.29	691.11	8.89
800	788.89	-0.29	789.18	10.82
900	881.91	-0.29	882.2	17.8
1000	987.07	-0.29	987.36	12.64

Surface=reflective,light=low				
Actual Z	observed	Offset:-	pos-off	abs error
0	0	0	0	0
100	95.03	-5.01	100.04	0.04
200	194.56	-5.01	199.57	0.43
300	292.78	-5.01	297.79	2.21
400	391.18	-5.01	396.19	3.81
500	491.26	-5.01	496.27	3.73
600	590.3	-5.01	595.31	4.69
700	688.82	-5.01	693.83	6.17
800	787.23	-5.01	792.24	7.76
900	881.01	-5.01	886.02	13.98
1000	985.62	-5.01	990.63	9.37

V.2.2 for a rigid body in 2D:

For dark surface with High lighting									
actual X	actual Z	observed X	observed Z	Offset along X	X-offset	Offset along Z	Z-offset	abs E X	abs E z
-500	500	-492.29	502.85	0.16	-492.45	0.59	502.26	7.55	2.26
-400	400	-381.98	412.19	0.16	-382.14	0.59	411.6	17.86	11.6
-300	300	-288.58	309.11	0.16	-288.74	0.59	308.52	11.26	8.52
-200	200	-195.82	204.54	0.16	-195.98	0.59	203.95	4.02	3.95
-100	100	-99.42	100.46	0.16	-99.58	0.59	99.87	0.42	0.13
0	0	0	0	0	0	0	0	0	0
100	100	97.98	100.69	0.16	97.82	0.59	100.1	2.18	0.1
200	200	199.54	197.18	0.16	199.38	0.59	196.59	0.62	3.41
300	300	303.3	291.15	0.16	303.14	0.59	290.56	3.14	9.44
400	400	406.61	386.36	0.16	406.45	0.59	385.77	6.45	14.23
500	500	499.27	495.01	0.16	499.11	0.59	494.42	0.89	5.58

For dark surface with low lighting									
actual X	actual Z	observed X	observed Z	Offset along X	X-offset	Offset along Z	Z-offset	abs E X	abs E z
-500	500	-492.49	502.64	0.91	-493.4	-0.45	503.09	6.6	3.09
-400	400	-382.39	411.6	0.91	-383.3	-0.45	412.05	16.7	12.05
-300	300	-287.23	309.16	0.91	-288.14	-0.45	309.61	11.86	9.61
-200	200	-195.09	204.91	0.91	-196	-0.45	205.36	4	5.36
-100	100	-98.07	100.09	0.91	-98.98	-0.45	100.54	1.02	0.54
0	0	0	0	0.91	-0.91	-0.45	0.45	0.91	0.45
100	100	99.75	99.2	0.91	98.84	-0.45	99.65	1.16	0.35
200	200	199.9	197.13	0.91	198.99	-0.45	197.58	1.01	2.42
300	300	304.01	291.69	0.91	303.1	-0.45	292.14	3.1	7.86
400	400	407.67	387.15	0.91	406.76	-0.45	387.6	6.76	12.4
500	500	499.67	497.5	0.91	498.76	-0.45	497.95	1.24	2.05

actual X	actual Z	observed X	observed Z	Offset along X	X-offset	Offset along Z	Z-offset	abs E X	abs E z
-500	500	-506.77	491.68	0.96	-507.73	1.59	490.09	7.73	9.91
-400	400	-397.4	385.16	0.96	-398.36	1.59	383.57	1.64	16.43
-300	300	-298.94	282.76	0.96	-299.9	1.59	281.17	0.1	18.83
-200	200	-195.46	184.67	0.96	-196.42	1.59	183.08	3.58	16.92
-100	100	-92.54	90.39	0.96	-93.5	1.59	88.8	6.5	11.2
0	0	0	0	0	0	0	0	0	0
100	100	108.15	98.05	0.96	107.19	1.59	96.46	7.19	3.54
200	200	203.6	202.61	0.96	202.64	1.59	201.02	2.64	1.02
300	300	303.32	302.56	0.96	302.36	1.59	300.97	2.36	0.97
400	400	401.93	393.46	0.96	400.97	1.59	391.87	0.97	8.13
500	500	499.28	498.32	0.96	498.32	1.59	496.73	1.68	3.27

For bright surface with low lighting									
actual X	actual Z	observed X	observed Z	Offset along X	X-offset	Offset along Z	Z-offset	abs E X	abs E z
-500	500	-510.68	491.68	1.2	-511.88	-3.4	495.08	11.88	4.92
-400	400	-400.68	385.16	1.2	-401.88	-3.4	388.56	1.88	11.44
-300	300	-301.57	282.76	1.2	-302.77	-3.4	286.16	2.77	13.84
-200	200	-198.12	184.67	1.2	-199.32	-3.4	188.07	0.68	11.93
-100	100	-93.98	90.39	1.2	-95.18	-3.4	93.79	4.82	6.21
0	0	0	0	0	0	-3.4	3.4	0	3.4
100	100	105.97	101.85	1.2	104.77	-3.4	105.25	4.77	5.25
200	200	201.05	206.32	1.2	199.85	-3.4	209.72	0.15	9.72
300	300	299.53	305.96	1.2	298.33	-3.4	309.36	1.67	9.36
400	400	398.12	398.82	1.2	396.92	-3.4	402.22	3.08	2.22
500	500	493.02	504.52	1.2	491.82	-3.4	507.92	8.18	7.92

V.2.3 For a rigid body in 3D placed on a "dark" surface in "dim" lighting:

offset along X=		-0.14						
offset along Y=		1.53						
offset along Z=		0.89						
actual X	actual Y	actual Z	observed X	observed Y	observed Z	s (actual)	s (observed)	abs error
100	248	100	94.38	250.41	97.81	285.4891	284.9202495	0.5688045
200	248	200	192.24	255.17	193.2	376.1702	373.3553087	2.8148656
300	248	300	298.87	258.61	290.81	491.4306	490.6861167	0.7444481
400	248	300	402.47	261.81	283.61	558.1254	557.6389595	0.4864745
100	190	100	85.99	187.32	102.79	236.8544	230.3233523	6.5310334
100	398	100	81.3	395.27	100.11	422.379	415.7764724	6.6025044
200	190	200	192.08	190.67	194.23	340.7345	333.1292065	7.6052943
200	398	200	175.07	398.63	197.97	488.2663	478.275551	9.9907698
300	190	300	296.56	194.56	288.59	464.8656	457.2588056	7.6067764
300	398	300	287.08	402.83	297.44	581.725	577.1979634	4.5270576

V.3 For a point object in motion over a "dark surface" in "dim" lighting

These results were obtained when the motion of the set-up shown in Fig. 8 was captured in a single take comprising of 5859 frames at 120 FPS and the frame wise data along each coordinate axis was exported from *Motive* in ".csv" format. The following is a glimpse of the observed position at few frames:

Format Version	1.21	Take Name	sing_mark_motiom_000	Capture Frame Rate	120	Export Frame Rate	120	Capture Start Time	2017-12-29 02.26.48 PM	Total Frames in Take	5859	Total Exported Frames	5859	Rotation Type	Quaternion	Length Units	Meters	Coordinate Space	Global
		Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker	Marker
		Unlabele	Unlabelec	Unlabelec	Unlabelec	Unlabeled:138	Unlabeled:138	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabelec	Unlabe
		8392B20C	8392B20C	8392B20C	8392B20C	8392B20CF49E35	8392B20CF49E3	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B20C	8392B2
		Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Position	Positio
Frame	Time	X(mm)	Y(mm)	Z(mm)	S(mm)	S_actual (mm)	abs_error(mm)		Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
0	0	-0.1429	0.161004	0.159717	0.268072	0.267029961	1.041873												
1	0.008333	-0.1417	0.161033	0.160903	0.268149	0.267029961	1.119208												
2	0.016667	-0.1401	0.160886	0.162122	0.267956	0.267029961	0.926419												
3	0.025	-0.1388	0.161012	0.163448	0.268173	0.267029961	1.142854												
4	0.033333	-0.1375	0.160772	0.164572	0.268031	0.267029961	1.000969												
5	0.041667	-0.1361	0.161092	0.165808	0.268286	0.267029961	1.256396												
6	0.05	-0.1347	0.160831	0.166857	0.268049	0.267029961	1.018679												
7	0.058333	-0.1335	0.161271	0.16811	0.268504	0.267029961	1.474219												
8	0.066667	-0.1323	0.161009	0.168923	0.268279	0.267029961	1.249394												
9	0.075	-0.1309	0.161082	0.169995	0.26831	0.267029961	1.280439												
10	0.083333	-0.1298	0.16124	0.170597	0.268227	0.267029961	1.196735												
11	0.091667	-0.1287	0.161157	0.171518	0.268249	0.267029961	1.218612												

VI Analysis and Inferences

The data obtained in Section V was analyzed in MATLAB, leading to the following inferences:

VI.1 for a point object in 1D:

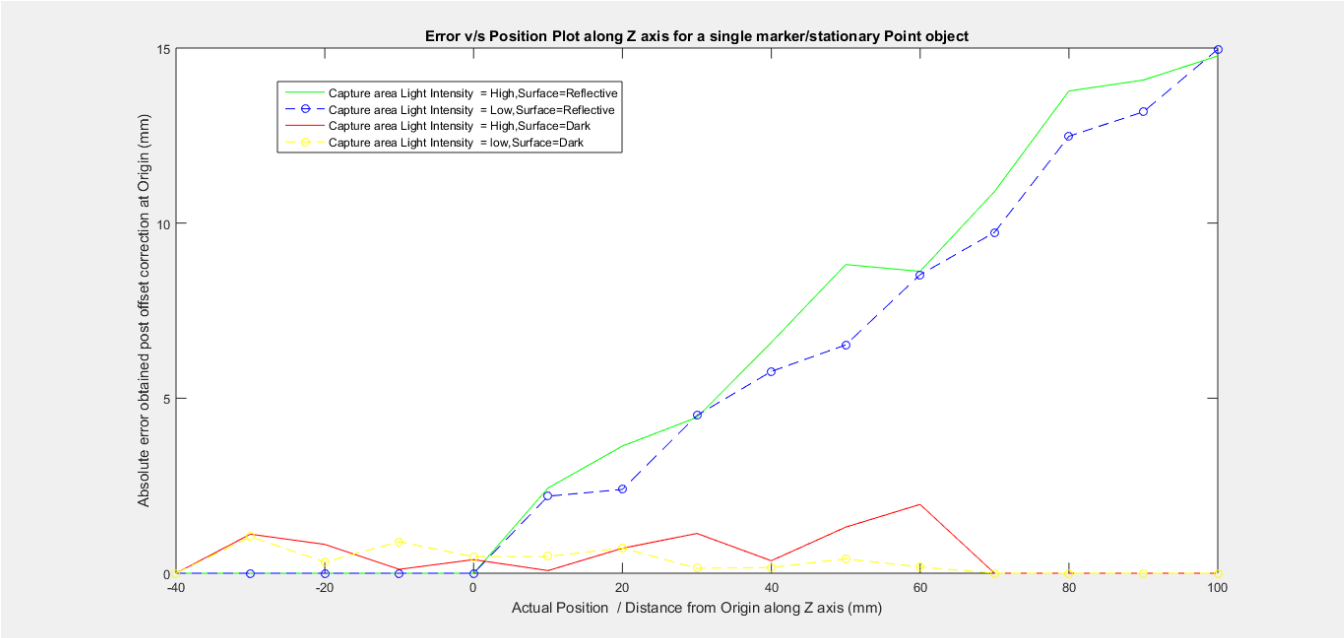

Fig. 10. MATLAB plot for data obtained in section V.1.1

We can conveniently infer that:

- → Error increases as we move away from origin
- → Dark surface with dim lighting is the best operational set-up
- → The maximum absolute error for best case is 1.045 mm

VI.2 For a point object in 2D:

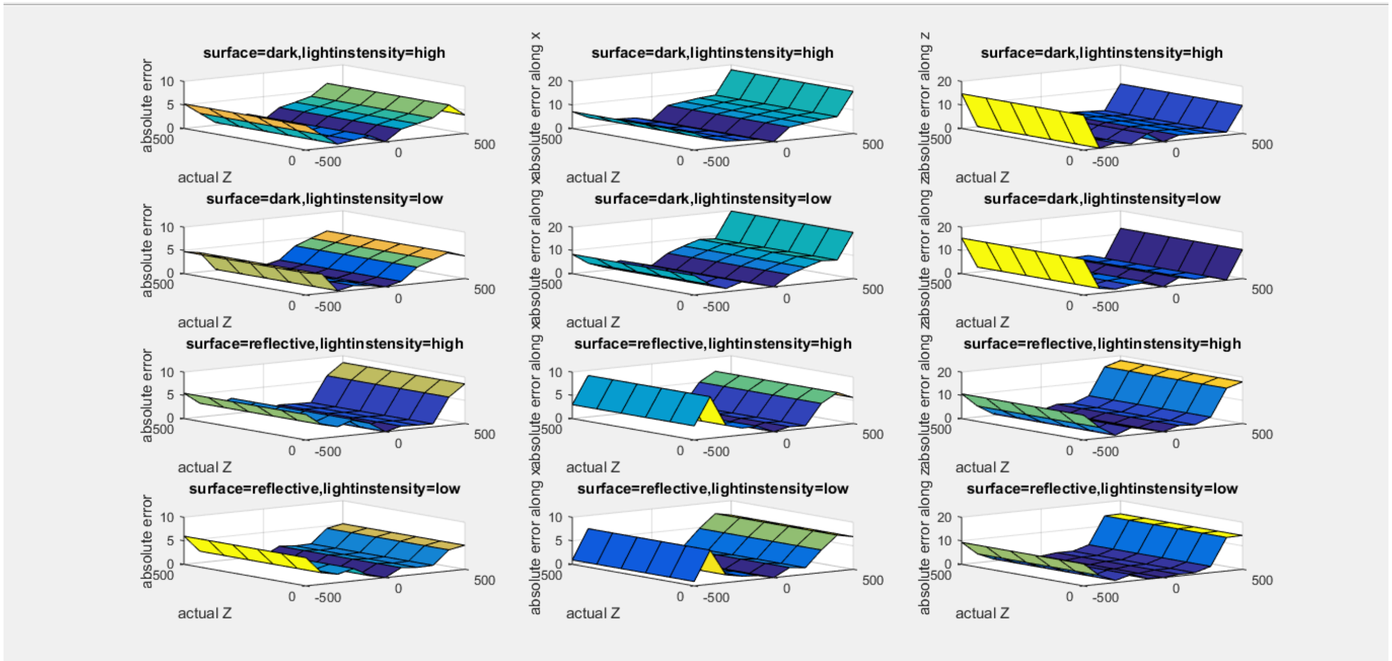

Fig.10 Surface plots for data obtained in Section V.1.2

These plots are consistent with the fact that:

→ Absolute Error increases as we move away from origin

→ Dark surface with dim lighting is the best operational set-up

VI.3 For a point object in 3D:

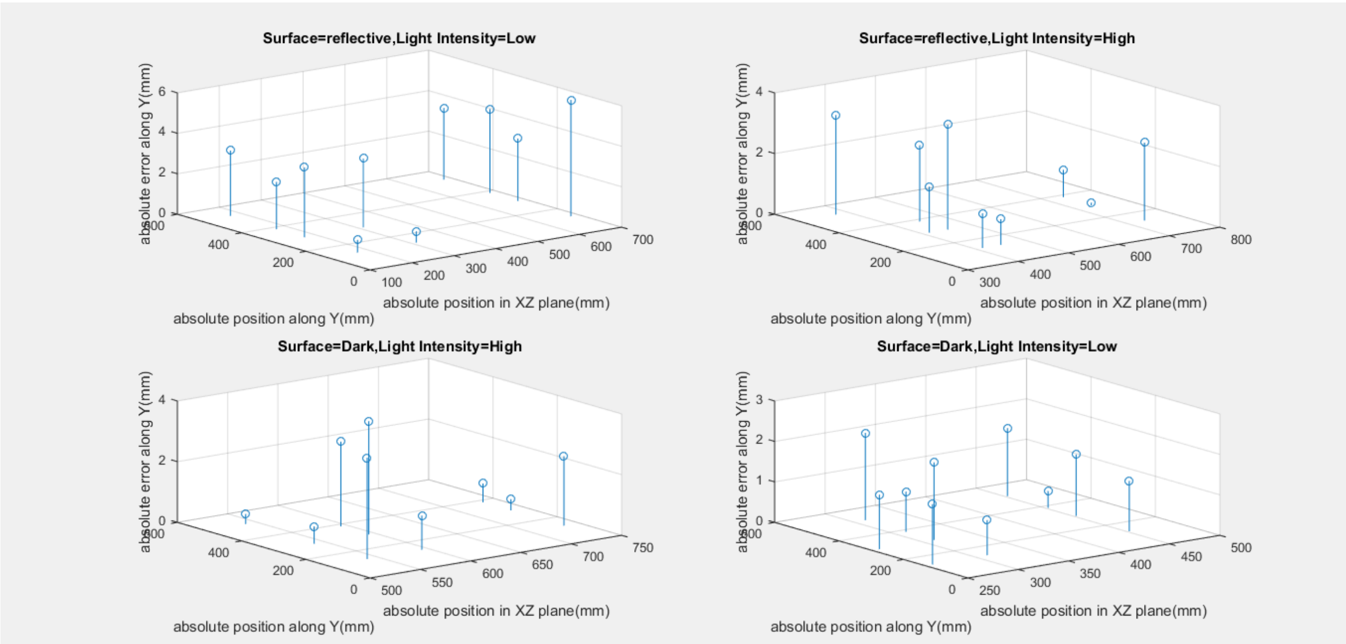

Fig.11 Stem plots for data obtained in Section V.1.3

These plots are also consistent with our observation of a Dark surface with dim lighting being the best condition for operation.

VI. 4 for a rigid body in 1D:

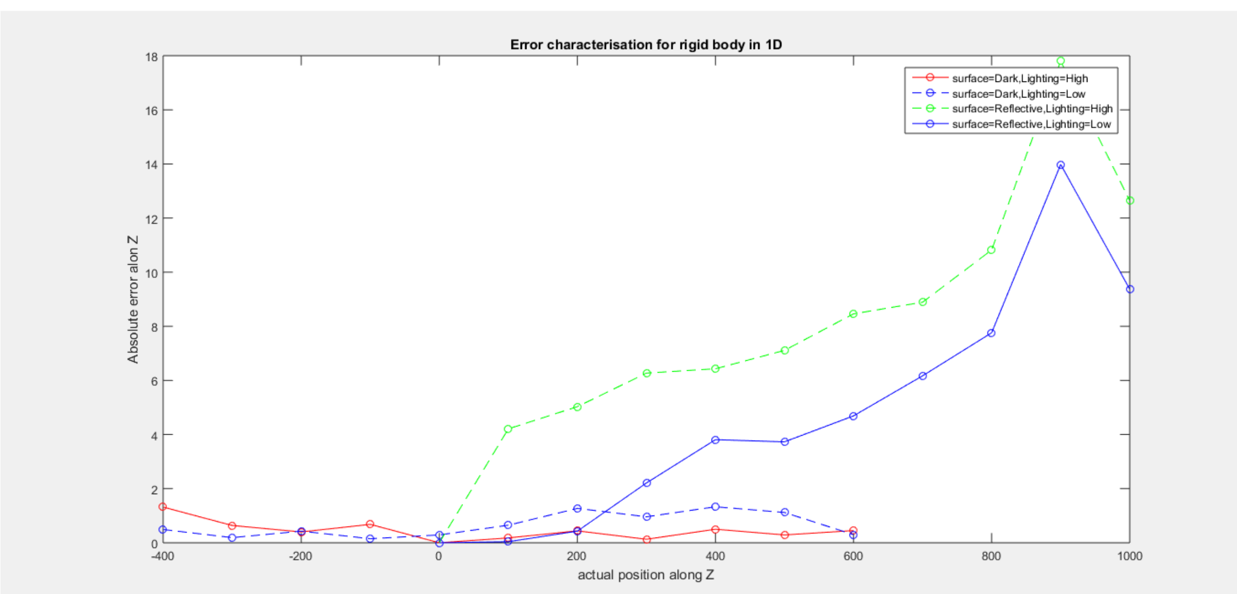

Fig.12 Plots for data obtained in Section V.2.1

We can conveniently infer that:

→ Error increases as we move away from origin
→ Dark surface with dim lighting is the best operational set-up
→ The maximum absolute error for best case is 1.33 mm

VI.5 for a rigid body in 2D:

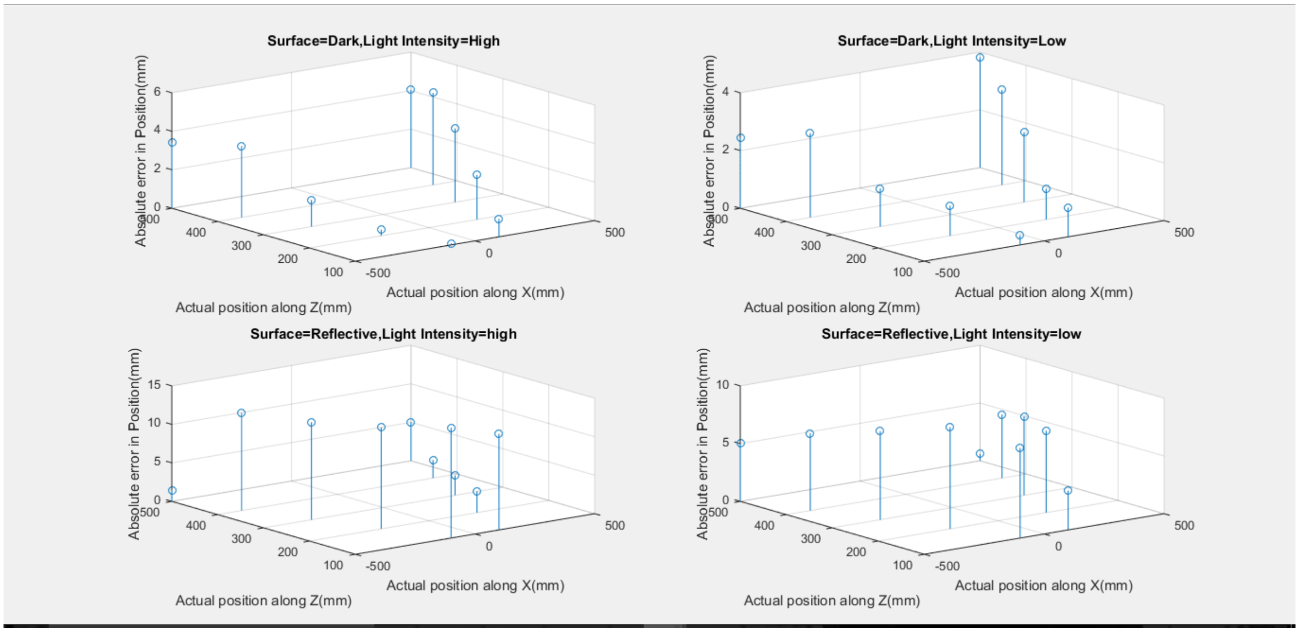

Fig.12 Stem Plots for data obtained in Section V.2.2

These plots are also consistent with our observation of a Dark surface with dim lighting being the best condition for operation.

VI.6 for a rigid body in 3D:

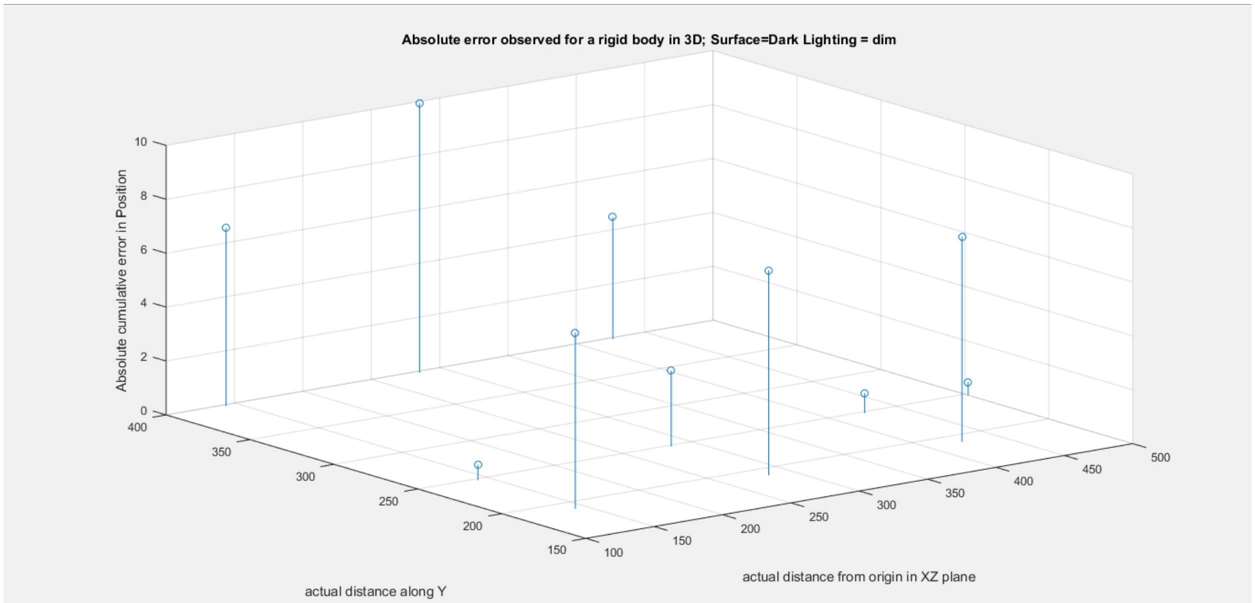

Fig.13 Stem Plot for data obtained in Section V.2.3

VI.7 for a point object in motion:

The setup shown in Fig. 8 was set into motion in the XZ plane on a dark surface in dim lighting and its motion was recorded in *Motive.* This data was then analyzed in a frame-wise manner in MATLAB.

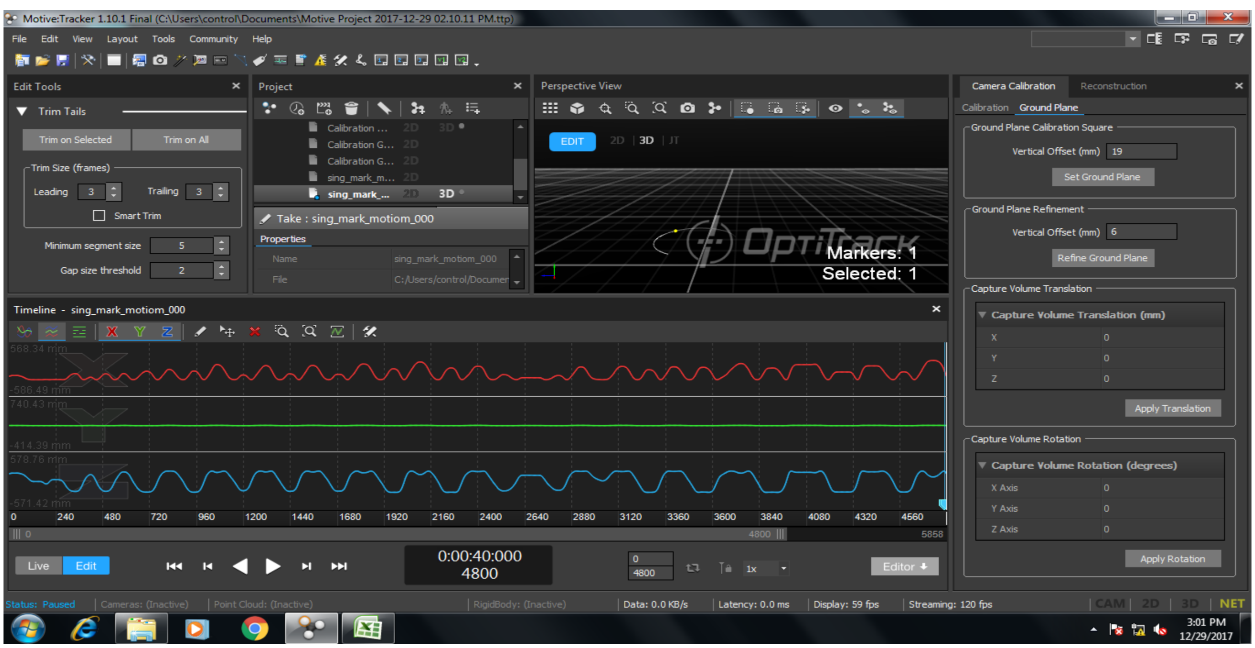

Fig.14 Recorded data for motion being played and plotted dimension-wise in Motive

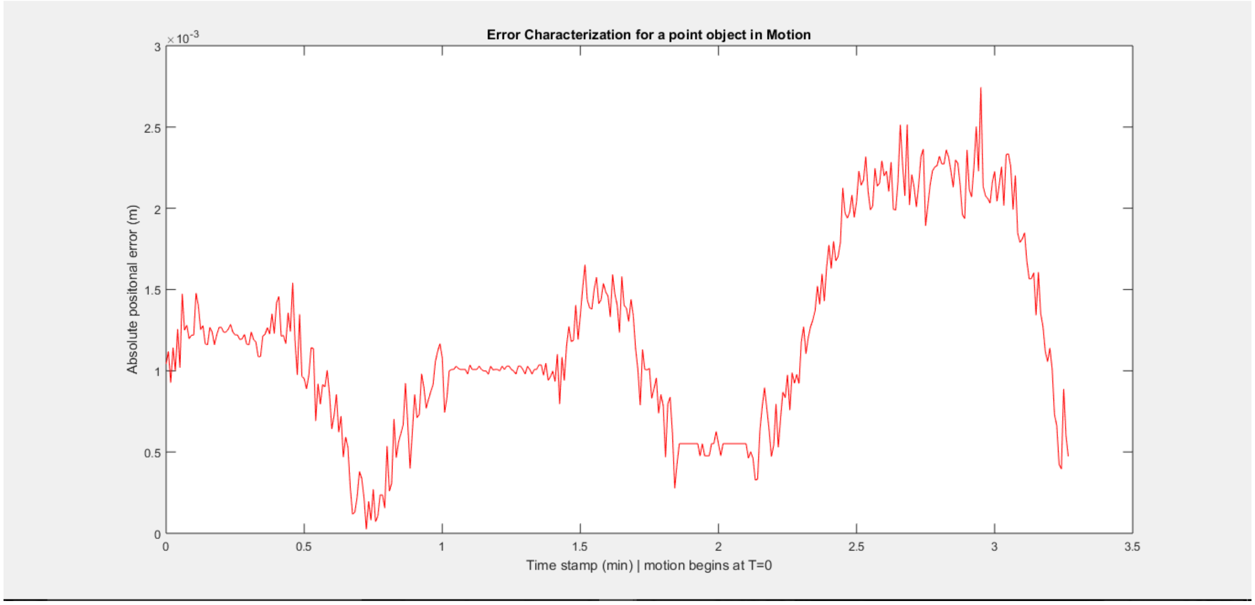

Fig.15 Plot for data obtained in section V.3

We can conveniently infer that:

- → The system is fairly accurate as the maximum error observed for the point object in motion is 2.8mm
- → The system is 'consistent' since there are no outliers / 'garbage' values
- → There is negligible compounding of error as in Fig. 14 the position along Y remains almost constant throughout the motion which is consistent with actual motion. Thus whatever error is observed along Y at the point of initiation is carried through the motion without any change.

VI.7. Test of repeatability:

The system was tested for repeatability by repeating the experiment for a point object in 2D on a dark surface with brightly lit capture volume for the same data points. The following results were obtained:

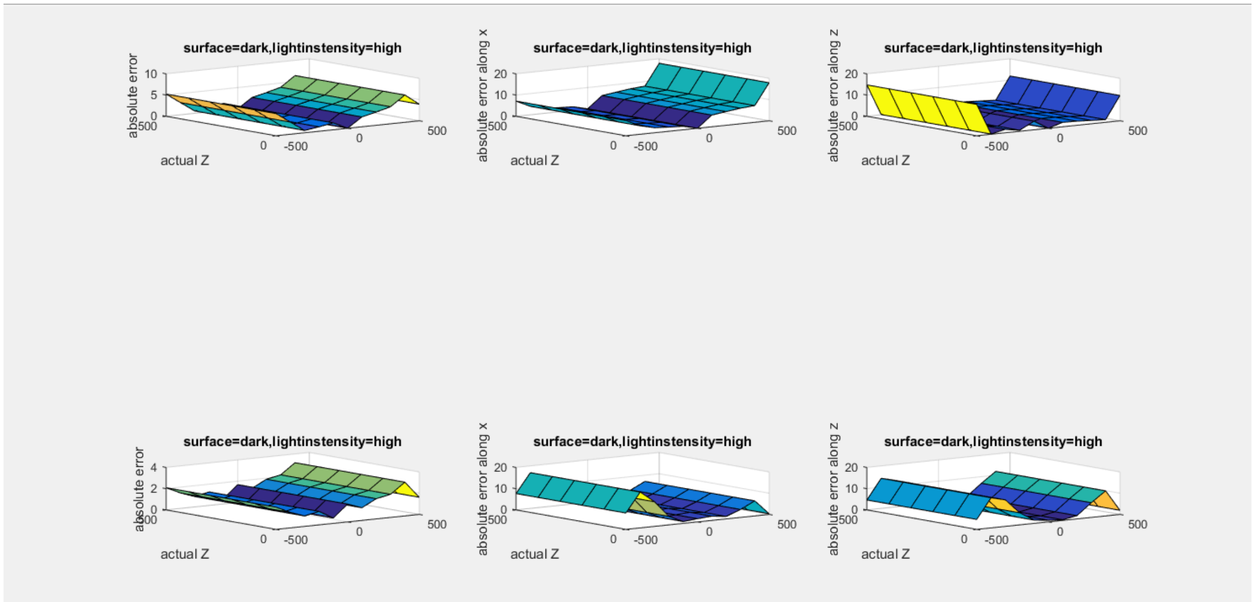

Fig.16 Surface Plots depicting results of the repeatability test

Upon careful observation, it becomes evident that results obtained were not exactly same however the trend for error values was largely similar. Also the change in absolute error in both the cases was <2mm. Thus the system can be termed “repeatable”.

VI.8. Analysis of trend in error with respect to distance from origin:

To get a better estimate of the variation in error as we move away for origin, determine the behavior of the system in various regions of the capture volume and for extrapolation of results obtained in this study we characterized the maximum error in various “range” of distances. The results were analyzed in MATLAB and the outcomes are as follows:

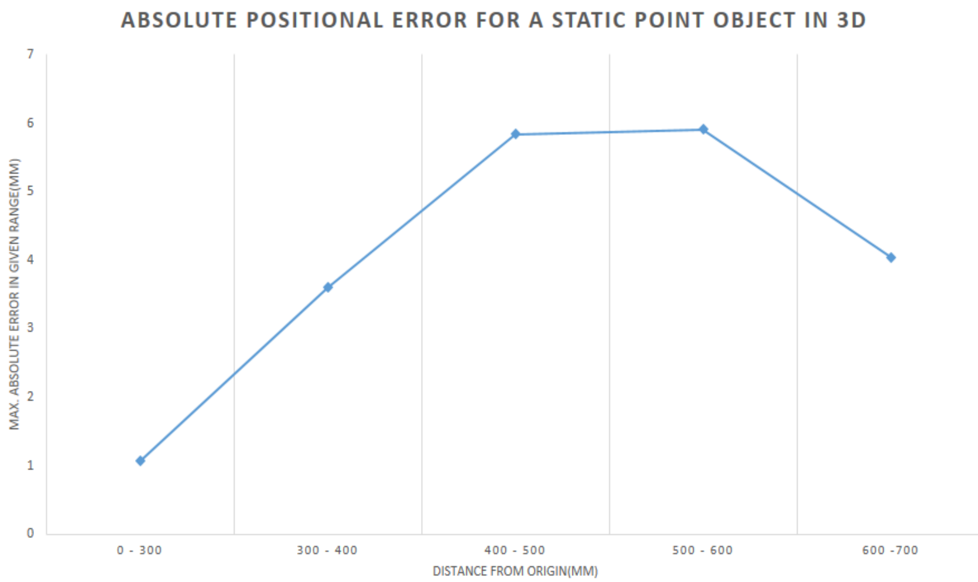

Fig.17. Analysis of absolute positional error for point object on a dark surface with dim lighting in 3D

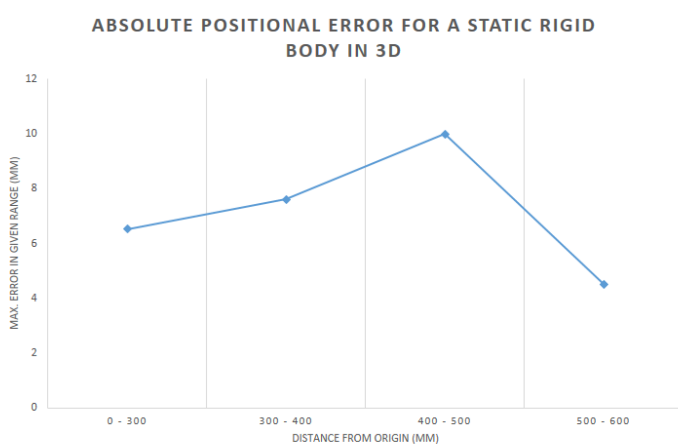

Fig.18. Analysis of Absolute positional error for a rigid body in 3D on a dark surface with dim lighting

From here we can conveniently conclude that:

→ The system is fairly "accurate" as the maximum absolute error in position obtained in this study was 1.1 cm for a rigid body and 5.99 mm for a point object

→ It is difficult to find a linear trend in the cumulative error with respect to distance, thus it can only be modelled by a non-linear function

VII Analytic Extrapolation of Inferences

The primary objective of this section of our work was to predict the error that might exist in a capture volume, larger than that surveyed during the course of this work. As inferred in section VI.8 we needed to model the error function non-linearly therefore we performed hit and trial using various functions in MATLAB's curve fitting toolbox and figured out that expression of the error function as a simple sinusoid yielded most plausible results. The following were the results obtained with 95% Confidence measure when the data obtained in section V.1.3 was extrapolated using non-linear regression:

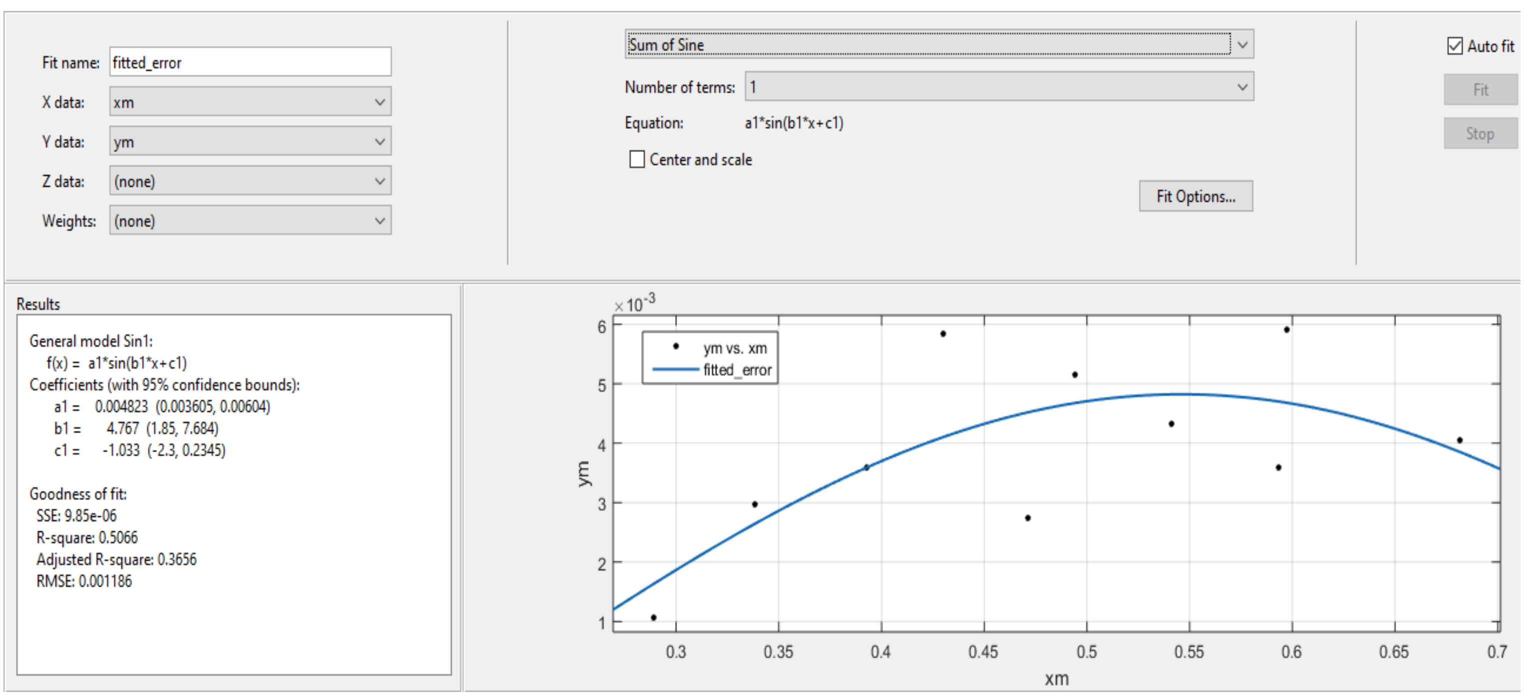

Fig. 19 Curve fitting on data points so as to obtain Mathematical function for extrapolation of results (xm= distane from origin in m, ym = absolute error in postion(m))

Therefore the equation governing the error as function of distance from the origin may be given by:

$$\boldsymbol{E} = \mathbf{0.004823} \times \mathbf{sin}\{(\mathbf{4.767} \times \boldsymbol{X}) - \mathbf{1.033}\} \quad - (1)$$

Where: X = Absolute distance in m.
E = Absolute positional error in m.

VIII Proposed laboratory set-up for future applications:

In this section we propose a new set up for the motion capture system at a dedicated laboratory with respect to the following parameters:

→ Selection of appropriate capture volume and origin
→ Camera placement and mounting
→ Finishing of capture volume flooring
→ Lighting arrangement in the capture volume
→ Methods to separate the capture volume from the remaining expanse of the Lab without disturbing the internal operations

VIII.1 Selection of appropriate capture volume and origin:

Fig. 20 The chosen area for installation of Motion Capture System in the new Lab. Complex with the selected origin and coordinate axes (X,Y,Z)

VIII.2 Camera placement and mounting:

As discussed in [5], all 8 cameras must be placed in a manner such that their field of view converges in the region which needs to be captured the most. The camera placement should be similar to the one shown in Fig. 21. Although the system can capture a volume of 7x7x2 m^3 however we propose to restrict the capture volume to 4x4x2 m^3 considering the various constraints in the Lab. Complex which has a ceiling height of 2.6m. Also the metallic structure mounted to support the false ceiling in the lab can be used to mount the cameras as per instructions given in [5].

Fig. 21 False-roof support structure that can be used for mounting

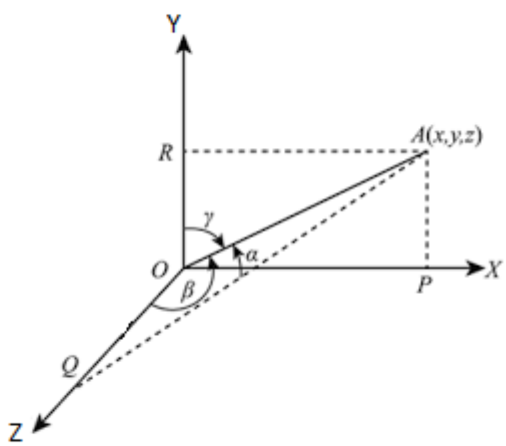

Fig. 22 Angle system for reference

We propose the cameras to be placed in the following manner :

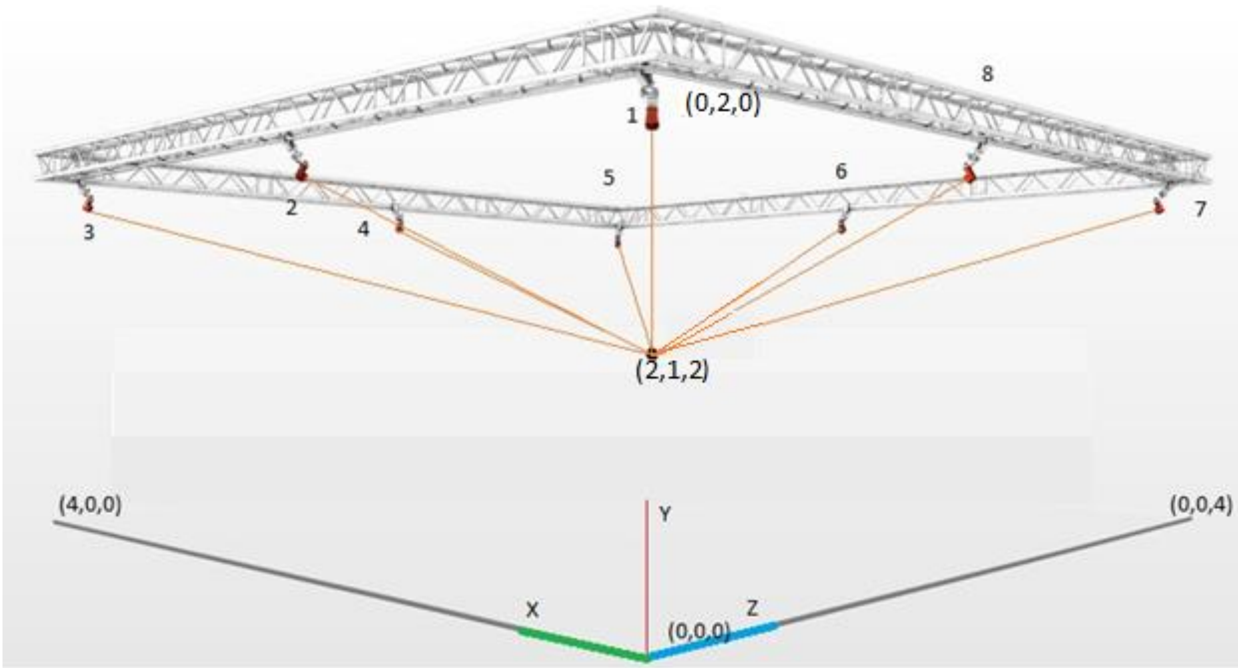

Fig. 23 Proposed Camera setup

Based on Figures 20, 21, 22 and 23 we propose the following coordinates for the camera mounts and angles for their Line of Sight (LOS) vectors. All distances are in meters and angles are in degrees.

Camera Number	X	Y	Z	α	β	γ
1	0	2	0	48.1897	48.1897	109.4712
2	2	2	0	90	26.5651	116.5651
3	4	2	0	131.8103	48.1897	109.4712
4	4	2	2	153.4349	90	116.5651
5	4	2	4	131.8103	131.8103	109.4712
6	2	2	4	90	153.4349	116.5651
7	0	2	4	48.1897	131.8103	109.4712
8	0	2	2	26.5651	90	116.5651

Table 2

VIII.3 finishing of capture volume flooring:

It is recommended that black rubber mats should be used to cover the flooring in the capture volume

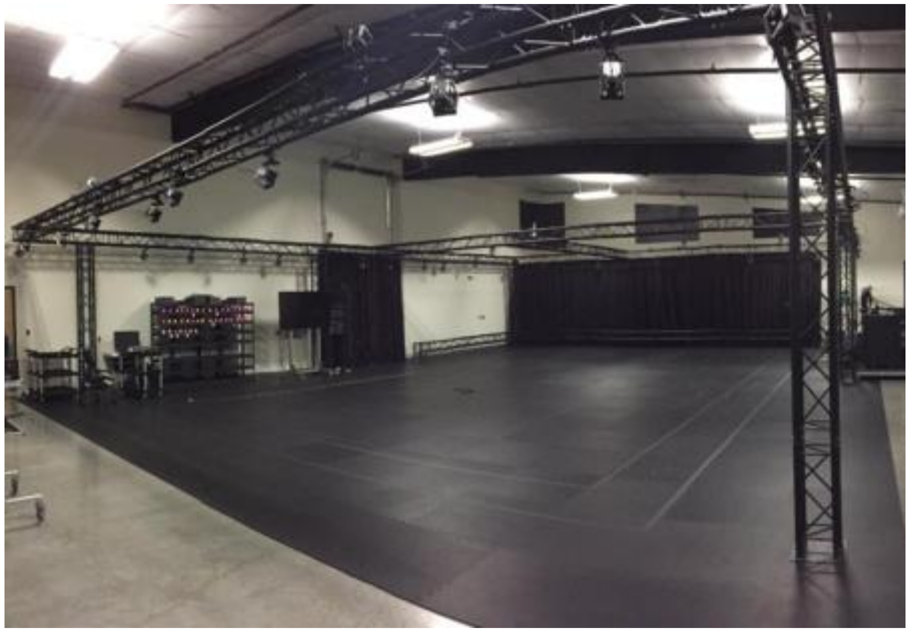

Fig. 24 Illustrative flooring finish and curtain separation

VIII.4 lighting arrangement in Capture Volume:

All windows within the capture volume should be covered with dark paper/ black curtains as shown in fig. 24 and ideally there should not be any lighting within the capture volume.

VIII.5 techniques for separation of capture volume:

It is highly recommended to use curtains as shown in fig. 24 for this purpose however for ease of operation from control station we may also go for the setup shown in fig. 25.

Fig. 25 separation of capture volume using translucent curtains

IX Conclusion

Based on the work done in section V, VI, VII and VIII we can easily conclude the following:

- → The system is fairly 'accurate' since the maximum absolute error in position during this study was 1.1 cm for rigid bodies and 5.99 mm for point objects in a capture volume of 1x0.5x0.51 m^3.
- → A dark surface having a mat finish along with least possible lighting in capture volume is the best condition for operation of the system
- → The system returns negligible outliers or garbage values
- → There is no compounding of error for objects under motion
- → The system is 'consistent' since the motion captured by the system is almost similar to the ground truth
- → Positional error increases along every individual axis as we move away from the origin however the cumulative error does not show a linear trend and is best modelled by equation 1.
- → The current set-up is not an ideal set-up yet the system gives fairly accurate results therefor the accuracy might improve drastically once it is setup properly
- → Based upon the current data we can say that the maximum possible positional error for the proposed setup shall be ~ 4.823 mm (from equation 1)

To sum it up, we can say that the *OptiTrack* motion capture system is an excellent tool for motion capture and if it is installed as per the recommendations made in section VIII it can be of great help towards testing and analysis of Control and Path Planning Algorithms.

X Future Work

There is an immense amount of work that can be done in the field of Motion Capture Systems however we have narrowed-in upon the following key tasks that need to be done with existing set-up:

- → Analysis of effect of Camera focus adjustment
- → Observation of system behavior at different capture frame rates
- → Analysis of motion of an object having more than 1 degree of freedom

Apart from this I propose the following work to be done if the project is further scaled:

- → Understanding the working principle of the cameras
- → Understanding the working principle of *Optihub* and development of a similar hub using discrete components
- → Analysis of raw data obtained by cameras
- → Development of an indigenous Multi-spectral Data fusion Algorithm.

XI References

[1] https://optitrack.com/public/documents/Flex%2013%20Data%20Sheet.pdf

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