PHOTON SCIENCE at STANFORD LINEAR ACCELERATOR CENTER

LUSI LCLS Ultrafast Science Instruments

ROBOT BASING AND WORK ENVELOPE FINAL REPORT	Report No. TR-391-003-18-0

This Design Report includes information from Square One Design Inc, The consulting engineering fIrm that completeD the study. It also includes a dialog between J Langton and Peter Carmen (of Square-One) clarifiying items and topics contained in the initial report submittal from Square One.

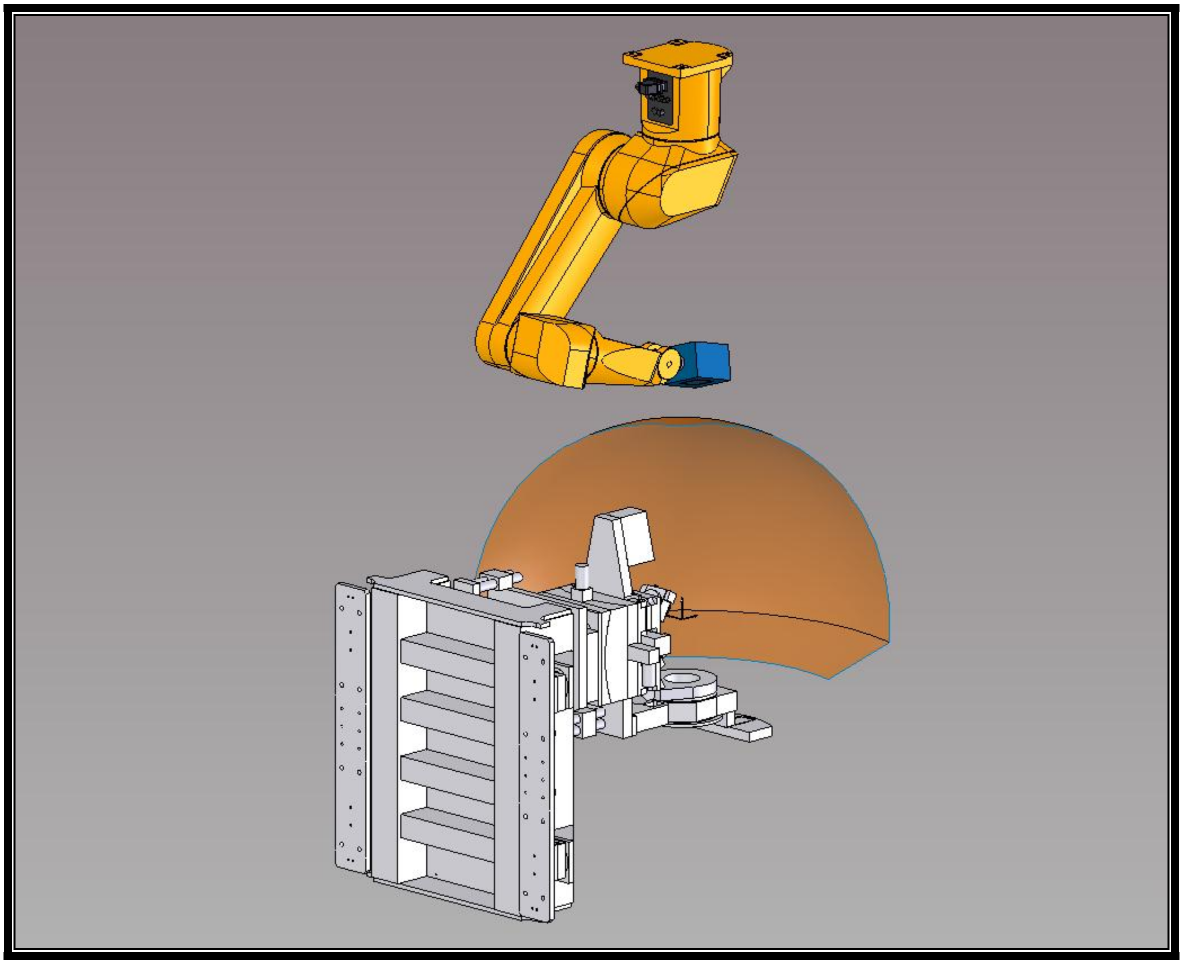
Initial report submittal is at beginning

JBL coments and questions are at the end in red.

Peter Carmen responses to those questions are interleaved in black among those questions and comments

This work was completed pursuant to Statement of work PS-391-000-95

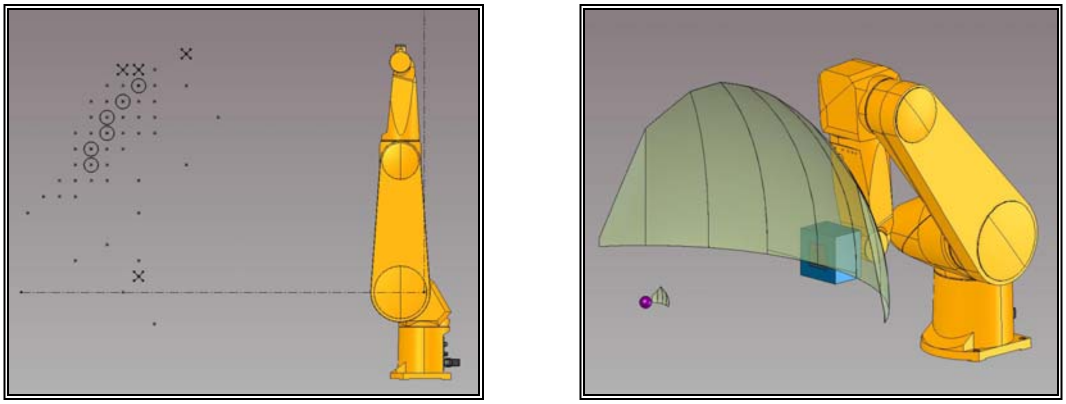
SQUARE ONE SYSTEMS DESIGN
Final Report
for
SP-391-000-62 R0
LUSI XPP Detector-Mover Engineering Specification
January 30, 2009



Over the course of the past few months, Square One's design team has investigated the use of a Staubli RX160L six-axis robot to serve as a "detector mover" for the LUSI XPP wide-angle detector. Previously, members of Square One's design team met with representatives from SLAC at Staubli's South Carolina facility to perform repeatability testing. Upon the successful conclusion of those tests, Square One began to consider how best to locate such a robot so that a detector mounted to the end of its arm could provide the coverage specified in *SP-391-000-62 R0*. Our design team utilized simulation software available from Staubli to track the movement of the robot's arm. The team initiated the investigation by writing software to move the robot's arm in such a way that the detector would move along a spherical surface, the center of which was the interaction point. Variables could be input by the user to allow changes in radius, azimuth, and elevation. The following discussion summarizes the four primary conclusions of our study.

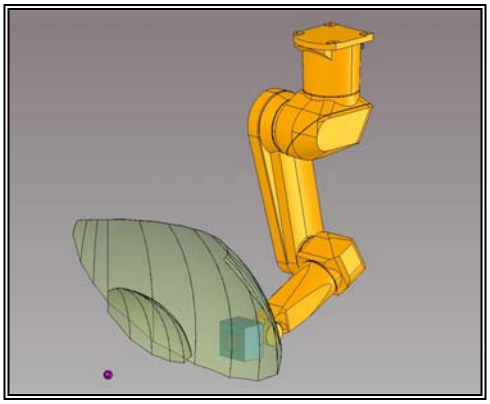
Conclusion #1

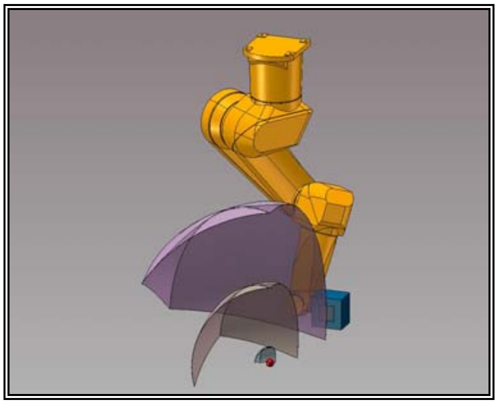
The first area that the design team focused on was obtaining full coverage of the primary interaction point (IP). Simulations initially utilized a floor-mounted robot with the interaction point in front of the robot as shown in the figure below.



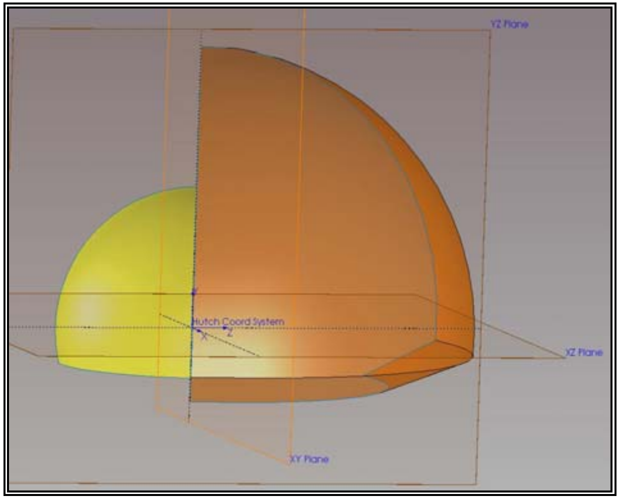
It can be seen that a variety of points were explored. In general, the points that provided the best coverage only did so for large radius spheres, i.e., r≥500 mm. Points that provided coverage down to 100 mm spheres provided only a fraction of the desired coverage.

As the design team gained familiarity with the simulator and the controlling software, it seemed apparent that better coverage would be obtained by mounting the robot to the ceiling and by changing the orientation of the detector relative to the robot arm. For example, the first simulations were conducted with the back of the detector mounted to the robot arm. It became readily obvious that mounting the side or top of the detector to the arm would provide better coverage than the back mount, as shown below.





Furthermore, placing the robot directly above the primary IP appeared to make better use of the robot's configuration to provide azimuth coverage. With the top of the detector mounted to the arm, it was able to cover the entire forward scattering range with respect to the elevation (-15° to +90°) for radii of 100 mm to 750 mm, and it covered from -5° to +90° for radii from 750 mm to 1000 mm. Full coverage could be obtained at the larger radii by extending the detector farther from the robot arm, thus increasing the effective arm length. To do this, attention must be paid to the published limits on joints 5 and 6 during the mechanical design of the detector. Full backward scattering coverage was also obtained. Due to the location of the IP on the z-axis of the robot, azimuth coverage ranged from -160° to +160°, the limits of the robot's joint 1. Perturbations of the IP off of the z-axis of the robot require other joints (in addition to joint 1) to move to provide azimuth coverage, so that there is full azimuth coverage, but less than the aforementioned -160° to +160°. Coverage for this mounting scheme, including both the forward (orange hemisphere) and backward (yellow hemisphere) scattering zones is shown below.



Conclusion #2

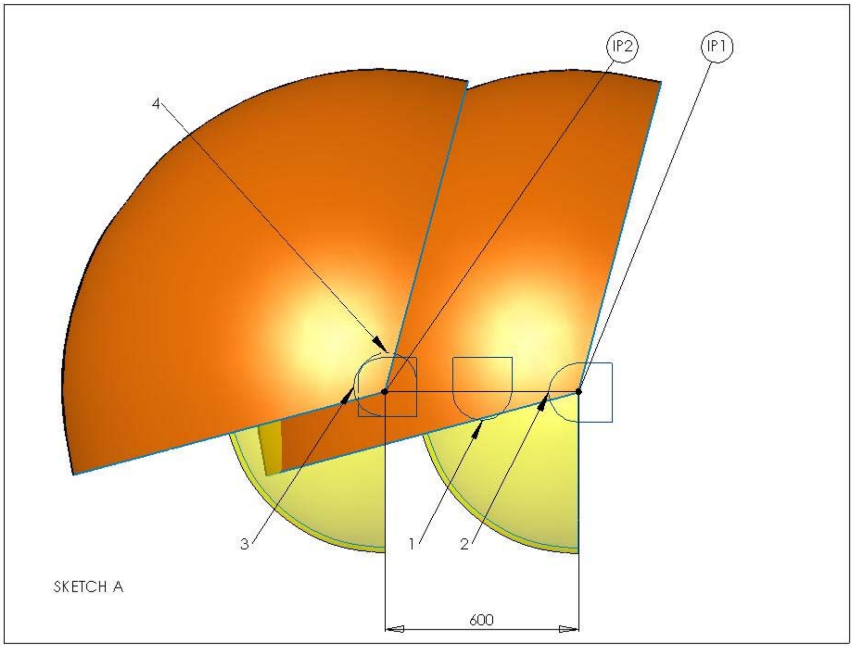
Secondly, the design team expanded the investigation of the primary IP to learn if full coverage could be maintained for movement of the IP resulting from changes in the x-ray beam. Due to the up-beam optical transport elements, the position of the x-ray beam, and therefore the location of the IP, can vary by up to 4 mm. In addition, experiments that require a down angle at the IP can result in a vertical offset of the IP of up to 30 mm. Combining the nominal variation due to upbeam elements with that due to the down angle locates the IP in a rectangular window 4 mm x 34 mm. The center of this rectangle is the reference used to position the robot. The table below shows elevation and radius ranges at the top, bottom, and center of the rectangle. Elevation and radius range are dependent on each other and also on the down angle offset. For purposes of this table, consider the top of the rectangle to correspond to a down angle offset of 0 mm, the center to be 15 mm, and the bottom 30mm.

Down Angle Offset (mm)	Radius (mm)	Min. Elevation (deg.)	Max. Elevation (deg.)	Azimuth (deg.)
0	100 to 780	-15	+105	-15 to +180
0	780 to 1000	-6	+105	-15 to +180
15	100 to 757	-15	+105	-15 to +180
15	757 to 1000	-5	+105	-15 to +180
30	100 to 730	-15	+105	-15 to +180
30	730 to 1000	-4	+105	-15 to +180

At any point within 4 mm x 34 mm rectangle, the detector (with the top face mounted to the robot arm) either can cover the full range of elevation for any radius less than 730 mm or can cover the full range of radii for any elevation ≥ -4°. As before, full elevation coverage at the larger radii can be obtained with use of an extended attachment for mounting the detector to the robot arm. Again, joint limits must be carefully heeded.

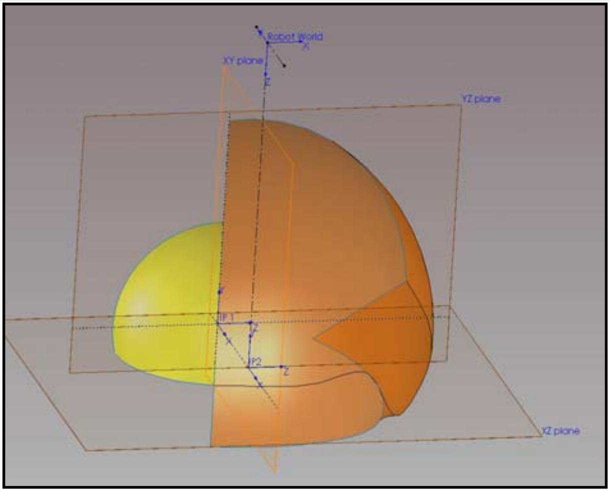
Conclusion #3

After the design team settled on a robot mounting location that maximized coverage of the primary IP, it then shifted its focus to changing that location such that coverage of both the primary and secondary IP's could be obtained. Four different robot locations were investigated, as shown in the following figure.



The first position located the robot directly between the two IP's. The second position located the robot over the primary IP, while the third located it over the secondary IP, and the fourth relocated it over the secondary IP but rotated 90° as compared with the third position. The fourth location yielded the best results. The chart and figure below show the coverages for this mounting location.

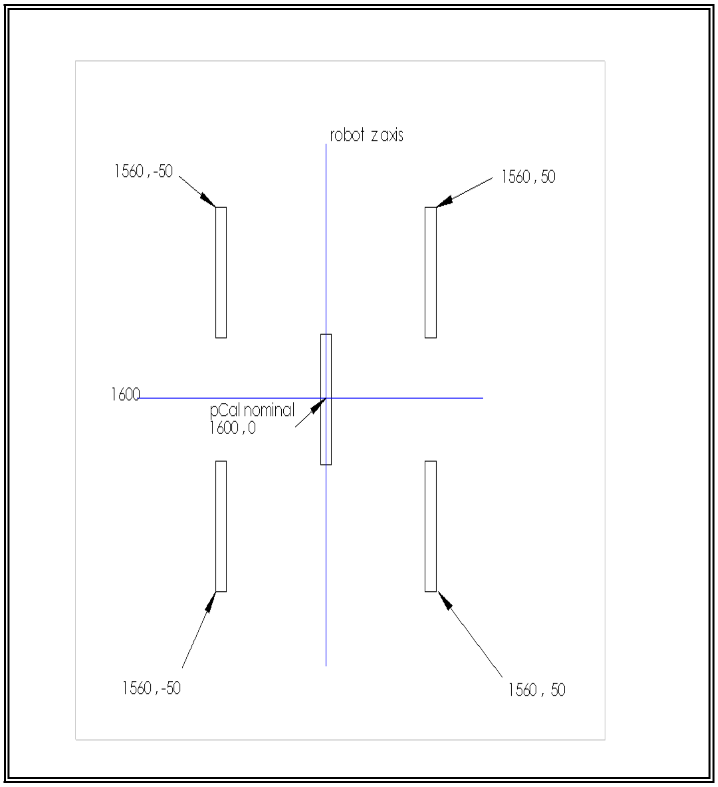
Azimuth (deg.)	Radius Range (mm)	Min. Elevation (deg.)
-15	100 to 527	-15
-15	527 to 1000	5
0	100 to 614	-15
0	614 to 1000	0
15	100 to 718	-15
15	718 to 1000	-4
30	100 to 830	-15
30	830 to 1000	-9
45	100 to 939	-15
45	939 to 1000	-13
60	100 to 1000	-15
75	100 to 1000	-15
90	100 to 1000	-15
105	100 to 1000	-15



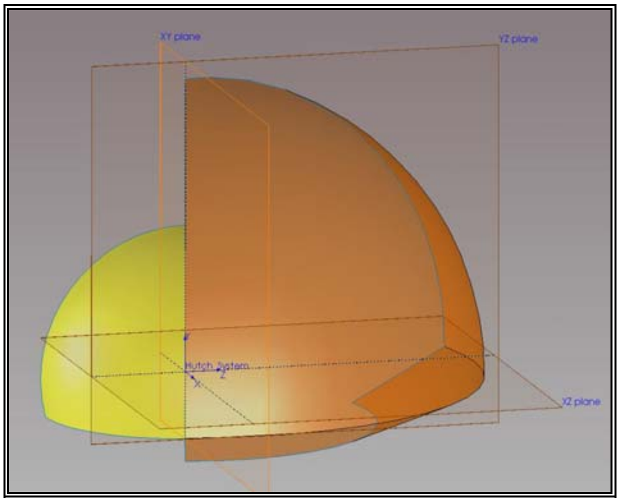
As for the other three locations that were considered in this section, the robot experienced dramatic configuration changes in order to provide the coverages shown above. Not only were these significant changes (i.e., the robot switched from being left-handed to being right-handed or vice-versa), but they occured multiple times during detector movement through the range of elevations. These changes will require a significant investment in software engineering to manage safely. On the other hand, moving the robot between two fixed positions provides full forward and backward scattering coverage with clean moves for both the primary and secondary IP's. As explained in the next section, there is relatively wide latitude in the accuracy with which the robot needs to be mounted.

Conclusion #4

Finally, the design team explored the accuracy with which the robot needs to be mounted relative to the IP in order to maintain maximum coverage. The figure below shows how the team explored the "worst-case scenarios." Four 4 mm x 34 mm windows are depicted, with the robot mounted in the center of the central window. Coverages at the four corners of the rectangle formed by the other four windows were checked. The detector could not be moved to provide absolutely complete coverage at each corner, but it could provide elevation coverage of at least -1° to +90°. Alternatively, the detector could provide full elevation coverage for any radius less than 666 mm.



Coverages at the worst position in this window are shown in the following figure.



Results indicate that offsets of the following result in no significant configuration changes:

x = 0 mm rx = 0°
y = ± 50 mm ry = 0°
z = 1600 ± 40 mm rz = 0°

This is generous tolerancing for robot mounting. The location of the IP relative to the robot can be measured in the field after the robot is installed, and appropriate adjustments can be made in the software setup for the robot.

Follow-up Questions

Staubli provides detailed specifications on how to mount the robot to the ceiling; however, details of this structural framework were not defined as part of this study. In addition, the design of this framework will depend upon whether there will be one or two mounting positions, as discussed under Conclusion #3. If two mounting positions are decided upon, design of the structural framework will need to include not only some means of indexing, but also a means to move the robot between the two locations.

While a ceiling mount affords the best coverage, it also facilitates meeting the stay clear requirements. However, simply mounting the robot to the ceiling does not insure that the robot arm and detector will not interfere with any of the other equipment in the heavily populated hutch. Now that the robot has been programmed to reach all of the required scattering areas, it will next be necessary to program it to reach these areas while handling the stay clear areas within the hutch. In addition, the robot software will need to include E-Stop considerations and to interface with the rest of the hutch controls.

JBL Comments:
So I'm 100% clear on the results described above:

1) Robot Location:

All results applying to the robot located above the sample, the position was with the center of joint 2 1600 mm above the nominal sample. Adding the Staubli dimension of 550mm (joint 2 to mounting surface) We would want the mounting surface to be 2150mm above the nominal sample position (?). Yes

With regard to conclusion #3 (ref: Sketch A):
Robot position 1 could provide nearly or total coverage or both sample locations (IP1 and IP2) but one or both sample location would require robot "configuration changes".

The table below shows the minimum Elevation for Az around an IP 300 mm to the side (Position 1 in Sketch A).

Az	0	30	60	90	120	150	180	210	240	270	300	330	360
Emin	-4	1	5	6	5	1	-2	2	-11	-13	-11	-8	-4

IP1 coverage is represented by Az from 180 to 360 (good)
IP2 coverage is represented by Az from 0 to 180 (poor)

The same statement could be made for the other positions.
Robot position 2, "looking at" IP1 doesn't require any "configuration changes". Correct
Robot positions 3 & 4 "looking at" IP2 doesn't require any "configuration changes". Correct

Summary Table

	IP 1		IP 2	
position	Coverage	Config changes	Coverage	Config changes
1 between IP1 and IP2	good	Yes	poor for elevations <0	yes
2 over IP 1	Good	no	Poor at low elevations	yes
3 over IP 2	Good . drops off at low E and high A	yes	Good	no
4 over IP 2	Slightly better than 3	yes	Good	no

2) Detector working distance:

My understanding is that in this document, all results are applicable with a 165 mm working distance for the detector, independent of the detector mounting (?).
The nominal detector is 200 mm square by 150 mm deep. The original 165mm working distance was for a "back mount" and provided for a 15mm thick adapter plate.
When the detector mounting was moved to the "side-top mount" the working distance remained at 165mm. The working distance wasn't changed to 115 mm (this would have left the same 15mm thick space, detector to robot). Either working distance value is good from the functional standpoint, I just want to be 100% clear.

For the top attachment the robot flange is parallel to the top surface of the detector, centered front to back (150mm/2 = 75mm), centered side to side, AND offset from the top by 15mm (flange to detector center = 200/2 + 15 = 115).

3) Robot configuration changes:

In conclusion #3, with regard to configuration changes, you say “they occurred multiple times during detector movement through the range of elevations”.

During your last visit we discussed these configuration changes and I was thinking that the robot had to make a configuration change before some elevation “on the way up”. And again at some elevation “on the way down”. Those elevations were not at the same. IE: there is an elevation window were the robot could be in either of the two configurations.

I agree about that. Too bad we can’t find a way to stay in the range where either configuration works.

Are there more than one configuration change required in either direction?

Sometimes. Usually, but not always, the same number of changes in either direction.

IE: For a given fixed azimuth, translating the robot up in elevation from max to min, would I need to do more than one configuration change? Sometimes

Same question for running the robot down, from max to min elevation. Sometimes

Would the answer to the above questions apply for all azimuths? Yes, but the details of where the changes occur varies by azimuth

Would the answer to the above questions apply for all four robot positions? Yes but the details are different

Below is a typical data set showing configuration changes and elevation ranges I did not include it in the report because I have so much data I couldn’t come up with a rationale for what to include.

A configuration change is indicated by cc between two elevation values. The elevation was changed in 15 deg steps.

Data Tables

Sketch A (4) Robot reaching IP1 from position over IP2

	X	Y	Z	rX	rY	rZ
pCal	0	600	1600			
Tool tT	100	0	75	0	-90	0

R	A	E: range	Max R E = -15
1000	-15	5to90to5	527
	0	0to75cc90to15cc0	614
	15	-4to75cc90to75cc60to-4	718
	30	-9to75cc90to45cc30tp-9	830
	45	-13to60cc75to60cc45to-13	939
	60	-15to60cc75to60cc45to-15	1000
	75	-15to45cc60to90to60cc45to-15	
	90	Ditto	
1000	105	-15to30cc45cc60to90to60cc45to0 cc-15	

500	105	-15 to 90 to-15	
	120	ditto	
	135	cc-15to45cc60to90to45cc30to-15	
	150	-15to60cc75to90to60cc45to-15	
	165	cc-15cc0to90to0cc-15	
	180	-15cc0to90to0cc-15	
500	195	-15to0cc15to90to15cc0to-15	

Summary

	A	Radius Range	E min
	-15	100 to 527	-15
		527 to 1000	-15 to 5
	0	100 to 614	-15
		614 to 1000	-15 to 0
	15	100 to 718	-15
		718 to 1000	-15 to -4
	30	100 to 830	-15
		830 to 1000	-15 to -9
	45	100 to 939	-15
		939 to 1000	-15 to -13
	60	100 to 1000	-15
	75	100 to 1000	-15
	90	100 to 1000	-15
	105	100 to 1000	-15

Robot reaching IP1 from position over IP2. Significant arm configuration changes required. We believe that these can be managed but some involve shoulder changes which will require large movements of the detector (slowly, of course).

Data Tables

Sketch A (4) Robot reaching IP2 from position over IP2

	X	Y	Z	rX	rY	rZ
pCal	0	+-50	1600+- 40			
Tool tT	100	0	75	0	-90	0

R	Y	Z	A (nu)	E: range (delta)	Max R E = -15
1000	-50	1640	-15	-3 No Sig Config Change	705
			0	-3	697
			30	-2	681
			60	-2	670
			90	-1	666
			105	-1	666

1000	50	1640	-15	-3 No Sig Config Change	689
			0	-3	695
			30	-4	712
			60	-4	724
			90	-4	7299
			105	-4	727
1000	50	1560	-15	-6 No Sig Config Change	80
			0	-7	813
			30	-8	796
			60	-8	842
			90	-8	847
			105	-8	846
1000	-50	1560	-15	-7 No Sig Config Change	822
			0	-7	813
			30	-6	796
			60	-5	785
			90	-5	780
			105	-5	781
			30	60 to 90 by 1 deg steps No singularities	

Summary

H offset	V offset	Radius	E min (delta)	E max	A (nu)
-50	+40	100 to 666	-15	90	-15 to 105
		666 to 1000	-15 to -1	90	-15 to 105
50	40	100 to 689	-15	90	-15 to 105
		689 to 1000	-15 to -3	90	-15 to 105
50	-40	100 to 800	-15	90	-15 to 105
		800 to 1000	-15 to -6	90	-15 to 105
-50	-40	100 to 781	-15	90	-15 to 105
		781 to 1000	-15 to -5	90	-15 to 105

The cells in red above represent the worst case.

pCal nominal is in the center of the IP window (30mm x 4mm).
For the range of data presented above the center can vary:
Vertically: +- 25 mm (hutch Y)
Crossbeam : +- 48 mm (hutch X)

No significant configuration changes occur for the range listed. The minimum elevation range is affected.

Variations in the mounting within these limits can be accommodated in software. Of course it is necessary to know what the variation is.