N91-20647

SSSFD MANIPULATOR ENGINEERING USING STATISTICAL EXPERIMENT DESIGN TECHNIQUES

John Barnes
Martin Marietta Space Systems

Abstract

The Satellite Servicer System Flight Demonstration (SSSFD) program is a series of Shuttle flights designed to verify major on-orbit satellite servicing capabilities, such as rendezvous and docking of free-flyers, Orbital Replacement Unit (ORU) exchange, and fluid transfer. A major component of this system is the manipulator system that will perform the ORU exchange. The manipulator must possess adequate toolplate dexterity to maneuver a variety of EVA-type tools into position to interface with ORU fasteners, connectors, latches, and handles on the satellite, and to move workpieces and ORUs through 6 degree-of-freedom (dof) space from the Target Vehicle (TV) to the Support Module (SM) and back.

Typical of study-phase contracts, a premium is placed on budget, time, and other resourçes to perform trade studies and investigations. Experiments requiring major laboratory hardware builds are almost precluded. Therefore, for this study, two cost efficient tools were combined to perform an investigation of robot manipulator design parameters. These tools are graphical computer simulations and Taguchi Design of Experiment methods. Using a high performance graphics platform, an off-the-shelf robot simulation software package, and an experiment designed with Taguchi's approach, the sensitivities of various manipulator kinematic design parameters to performance characteristics are determined with minimal cost.

Taguchi's methods have been applied to many research and manufacturing problems, but seldom to system design issues. To our knowledge, this is the first application of Taguchi's methods to a manipulator design problem.

1.0 Introduction

Since the SSSFD is to be a minimum cost, high reliability program, the contractor is encouraged to utilize hardware elements of the Flight Telerobotic Servicer (FTS) robot with as few modifications as possible. The challenge, then, is to identify potential areas of manipulator modification which will yield the greatest increases in the quality characteristics of importance to the SSSFD mission. This paper documents the definition, conduct, results, and conclusions of our investigation of manipulator design features, using Taguchi methods for experimental design.

2.0 Performance Characteristics

The SSSFD manipulator will eventually be required to service a variety of satellites with a wide range of ORU sizes, fastener types, and access configurations. It, therefore, will likely require at least 6 dofs, and as much dexterity as possible to be adaptable to changing workspace conditions.

The ultimate purpose of our investigation, then, is to identify potential areas of modification of the manipulator kinematic design which would yield the greatest increase in toolplate dexterity. From our experiences simulating robotic tasks for the FTS program, we defined dexterity as the included angle of tool orientation about a point in the workspace where at least 12" of approach length is available along any ray within that angle. This definition relates to the requirement to position an 8" long tool or end effector to within a 4" approach to the fastener, where final alignment can be effected to interface properly. Since the manipulator's dexterous capability varies over the points in the workspace, it was decided that maximizing the <u>average</u> included angle over these four points will provide the best conditioned workspace for general applications. Our quality characteristic, then, was the <u>included angle of orientation of the toolplate averaged over multiple workspace points</u>.

To gather data, we used the Approach Length Ray Graph (ALRG) generation capability of the SILMA, Inc., CimStation robotic simulation software running on a Silicon Graphics, Inc. IRIS 4D workstation. ALRGs [1] graphically depict the approach length and orientation capabilities at points of interest within any chosen plane. In addition, the software creates data files of the search data for analysis.

In an initial investigation, we chose four points within a normal workspace envelope to take data; three of which were at roughly 75% of total manipulator reach and the fourth at a point in the center, but 20" closer to the base. The three points at 75% reach were defined in the center, upper left, and lower right extremes to get full coverage of the workspace. The results of this initial work identified joint travel limits - especially wrist yaw and pitch joints - as the only significant factor affecting dexterity. It was felt, though, that we did not adequately address ranges of total arm length versus wrist length in this investigation. Also, we did not include interactions between factors or the effects of any noise sources in this experiment. Therefore, a second experiment was designed to study the effects of the significant factors from the initial results as well as interactions and a source of process noise. This paper discusses the details of the second investigation.

At this point, we have not identified the values associated with a Loss Function, although it is clear our Loss Function is based on "Larger is Best," since we want to maximize dexterity. We simply have not quantified the losses resulting from a lack of dexterous capability, although that may be a future task. Our initial interest is to identify the design areas in which to focus our resources.

3.0 Design Factors

The baseline FTS manipulator, shown in Figure 1, is a 7R (7-dof, revolute jointed) robot with six actively controlled joints. Its degrees of freedom are (1) indexable shoulder roll, (2) shoulder yaw, (3) shoulder pitch, (4) elbow pitch, (5) wrist pitch, (6) wrist yaw, (7) wrist roll. The shoulder pitch is offset 9" from the shoulder yaw axis. The baseline upper and forearm link lengths are 18" each. The wrist pitch-to-yaw and yaw-to-tool plate link lengths are 4" and 10.25" respectively. The shoulder roll joint can be rotated through 180° to effect an "elbow up," "elbow out," or "elbow down" orientation, or any angle in between. In theory, the teleoperator will place the shoulder roll joint at an optimum angle for performing a given task prior to initiating that task motion.

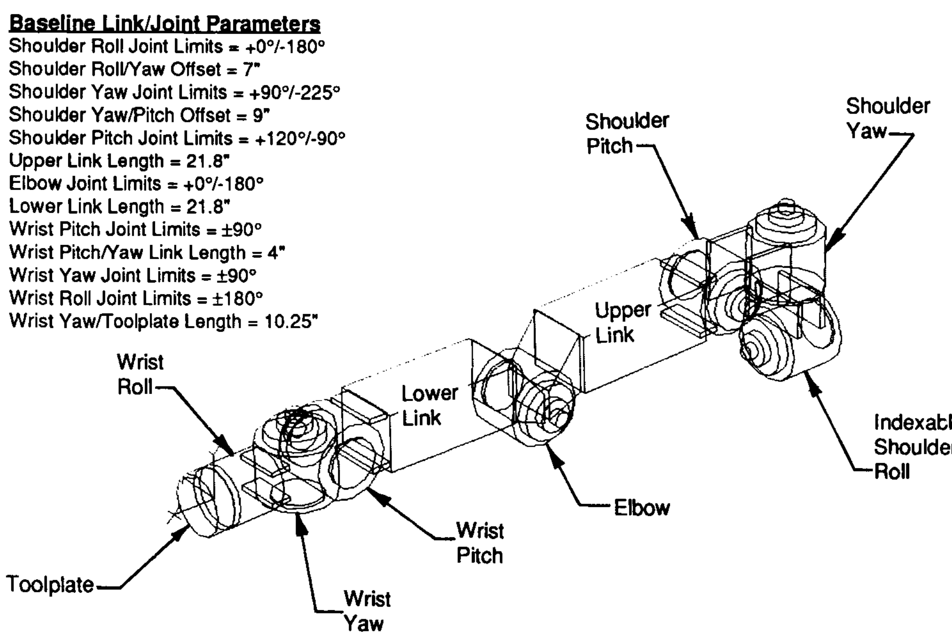

Figure 1 Baseline FTS Manipulator Design

For the experiment, we chose to leave the shoulder link lengths and offsets, and the ordering of the first four joints as they are in the FTS baseline, since they basically perform the function of positioning the wrist and end effector, and don't have a major effect on dexterity. Based on lessons learned from previous task simulations, we defined four design factors with potential to impact dexterity. Three of these concern the wrist design, and the fourth addresses the relative link lengths. The four design factors used were: (1) wrist (or hand) length, measured as the distance from the most proximal joint axis to the toolplate, (2) shoulder pitch and wrist pitch and yaw joint limits, (3) wrist joint configurations, and (4) ratio of arm positioning link lengths to orienting link lengths (shoulder+upper+forearm length to wrist length).

A source of "noise" that could have an impact on available dexterity is the shoulder roll joint position. If we assume that the operator may have less than perfect apriory information on the optimum shoulder roll position for that task, then its position relative to the optimum will vary, and have an effect on dexterity. Also, the shoulder roll joint position may be selected to satisfy requirements other than dexterous capability, such as force transmission or obstacle avoidance. We, therefore, selected three positions for the shoulder roll joint noise variable: (1) 0° (elbow up), (2) 5° elbow outward, and (3) 15° elbow outward.

4.0 Experiment Design

In an initial investigation of an issue, it is recommended [2] to evaluate many design factors at only a few levels. Then, with the results of the first experiment, perform another experiment on the few significant factors at more levels. Since this was our first investigation of FTS manipulator modification effects, we chose to use the four design factors described in Section 3.0 at only two levels, along with the shoulder roll joint "noise" factor in an outer array. These four design factors at their two level variations are shown in Figures 2-5.

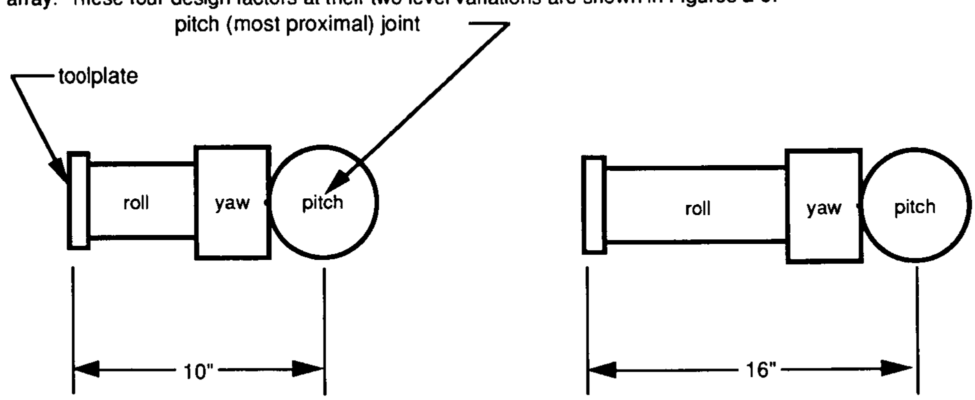

Figure 2 Wrist Length Factor at 10" and 16" Levels

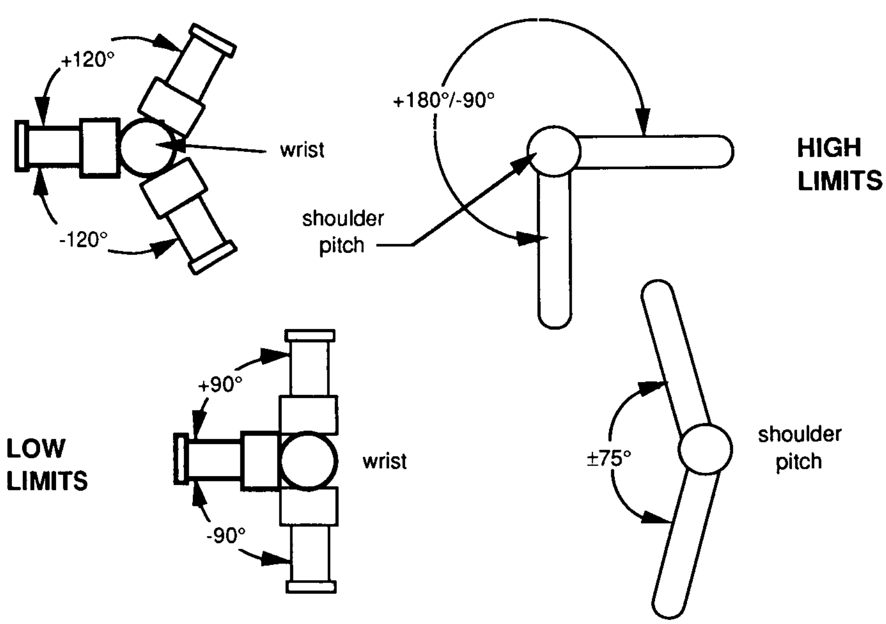

Figure 3 Joint Limits Factor at High and Low Levels

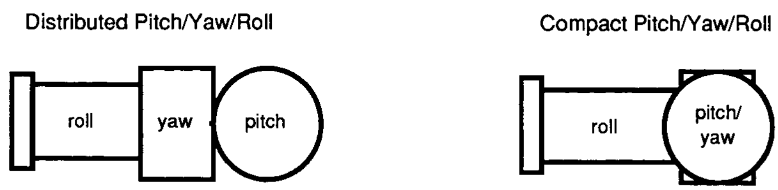

Figure 4 Wrist Joint Configuration Factor at Distributed and Compact Levels

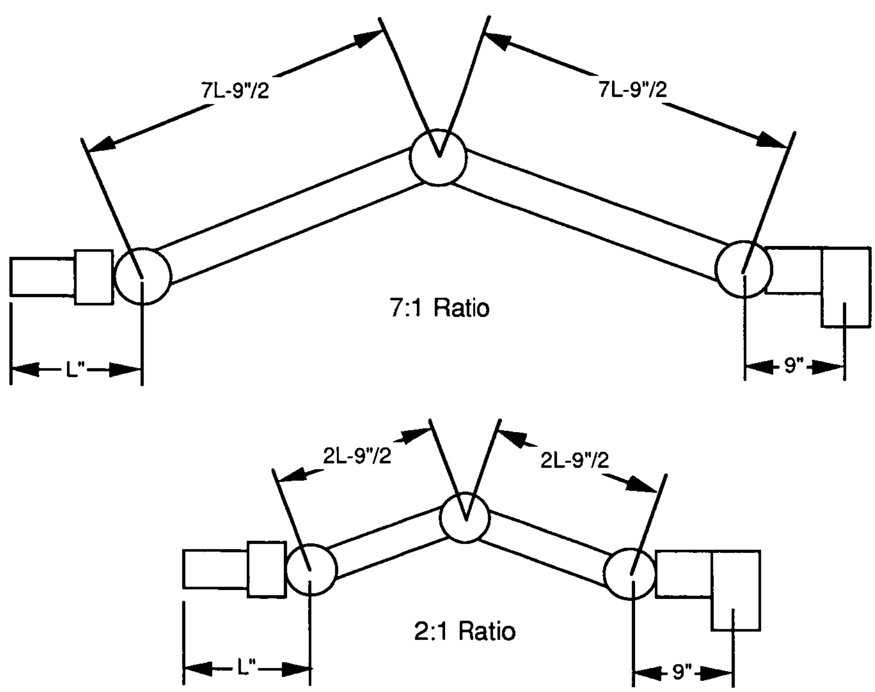

Figure 5 Positioning/Orienting Link Ratio Factor at 7:1 and 2:1 Levels

To fully analyze all possible combinations of these factors at two levels (full factorial experiment) would require creating and collecting data on $2^7 = 128$ different arm configurations. A much more efficient approach developed by Dr. Genichi Taguchi [3] uses orthogonal arrays (or Hadamard's matrices) to define fractional factorial experiments (FFE's) which produce results sufficiently close to those of a full factorial experiment with greatly reduced effort and cost.

For our experiment, we chose to use the $L_8(2^7)$ orthogonal array with an exterior noise array consisting of our three shoulder roll joint positions. This design also allows us to investigate the significance of interactions between some of the factors, specifically between wrist length and joint limits, wrist length and wrist joint configuration, and joint limits and wrist joint configuration. The specific manipulator configurations used in the experiment trials are given in Table 1.

trial #	wrist length	joint limits	wr design	link ratio	shoulder roll position 0°	5°	15°
1	10"	high	compact	2:1			
2	10"	high	distrib	7:1			
3	10"	low	compact	7:1			
4	10"	low	distrib	2:1			
5	16"	high	compact	7:1			
6	16"	high	distrib	2:1			
7	16"	low	compact	2:1			
8	16"	low	distrib	7:1			

Table 1 Manipulator Experimental Configurations

These manipulator trial configurations were then modeled in the CimStation simulation environment on a Silicon Graphics, Inc. (SGI) 4D/80GT IRIS graphics workstation. The CimStation package contains an application which, when given a manipulator kinematic description, will search for a closed-form inverse kinematic solution. Using this feature, we were able to find closed-form solutions for each arm, which enhanced the validity of our data by guaranteeing all feasible solutions were found for each toolplate position/orientation. Figure 6 shows an example of the CimStation work cell used for each experimental run. The individual manipulator models were installed into the cell and commanded to move their toolplate frame to the appropriate workspace frames, where the ALRG data was generated.

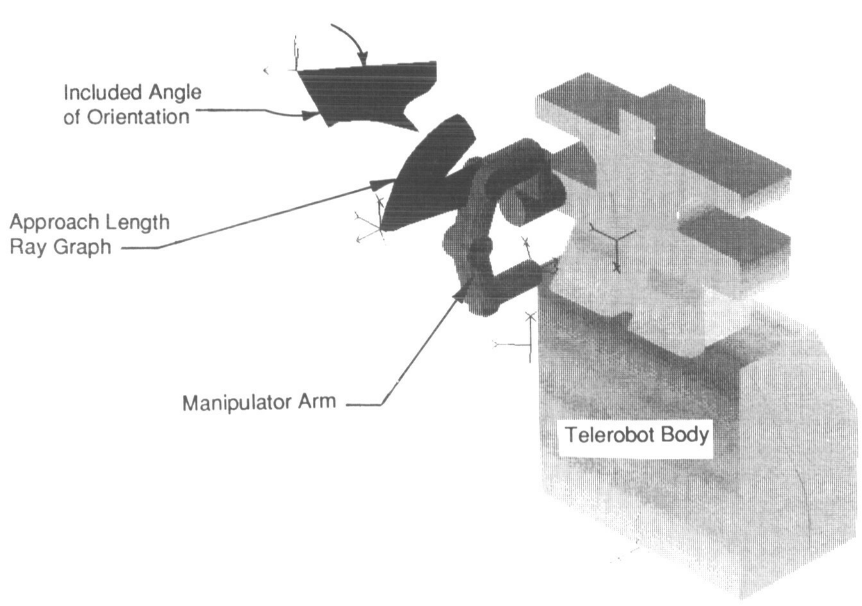

Figure 6 CimStation Workcell for Data Generation

5.0 Experimental Results

Preliminary investigations determined that the dexterity data results are insensitive to the plane (vertical or horizontal) in which the ALRGs are generated. Therefore, data for this experiment were generated in only the vertical plane. The raw average angle data for each of the eight trials is given in Table 2.

	Shoulder	Roll	Position
Trial Number	0°	5°	15°
1	72°	104.8°	102.2°
2	213.8°	213°	191°
3	108.6°	110.8°	111.8°
4	23.6°	31.2°	24.6°
5	221.2°	220.2°	199°
6	116.2°	98.6°	98.2°
7	25.6°	14.8°	13.6°
8	129.8°	126.2°	103.2°

Table 2 Average Dexterous Angle Data for Each Trial

For each of the individual factors and interactions, the raw average angle data are given in Table 3.

noise & factor lvl	wrist length	joint limits	wl x jl	wrist design	wl x wd	jl x wd	link ratio
0° lvl 1	104.50°	155.80°	110.30°	106.85°	106.65°	111.65°	59.35°
0° lvl 2	123.20°	71.90°	117.40°	120.85°	121.05°	116.05°	168.35°
5° lvl 1	114.95°	159.15°	114.70°	112.65°	110.10°	120.60°	62.35°
5° lvl 2	114.95°	70.75°	115.20°	117.25°	119.80°	109.30°	167.55°
15° lvl 1	107.40°	147.60°	102.50°	106.65°	103.85°	107.25°	59.65°
15° lvl 2	103.50°	63.30°	108.40°	104.25°	107.05°	103.65°	151.25°

Table 3 Average Dexterous Angle Data for Each Factor and Interaction

To visualize the results in Table 3, the average response data at each level were plotted at each shoulder roll position, providing a graphic understanding of the effects of level and noise variation on each factor. Figure 7 shows these plots for each design factor and interaction, using a common ordinate axis scale to facilitate direct comparisons of factor responses.

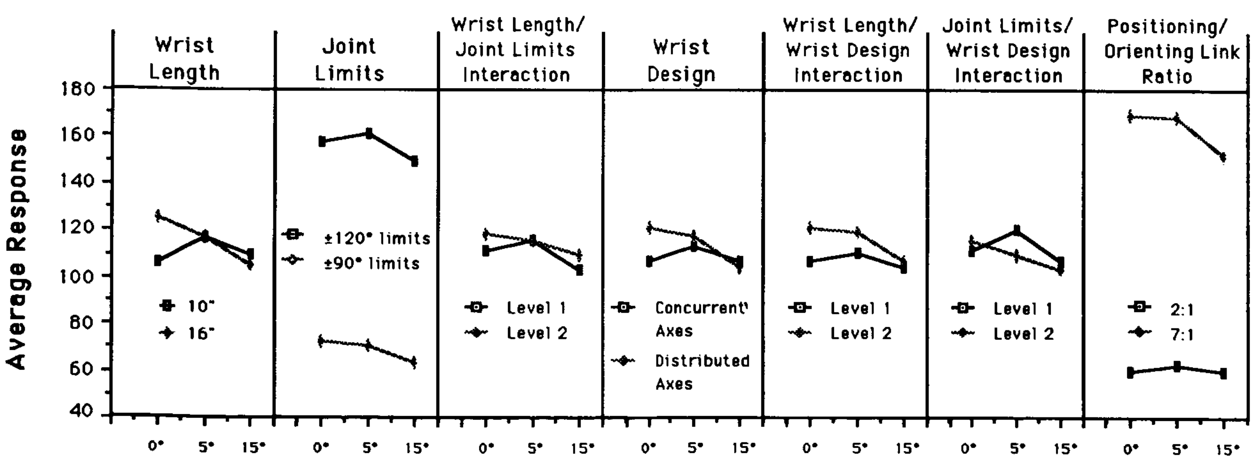

Figure 7 Average Response Data for Each Factor & Interaction

These plots indicate that the only factors or interactions which respond significantly to the changing levels are the Joint Limits and Positioning/Orienting Link Length Ratio factors. They also show that these factors do not respond significantly to the noise source within the 0° - 15° shoulder roll range. The next step was analysis of the data variance to quantify and verify these graphic results.

6.0 Analysis of Variance (ANOVA)

To quantify the sensitivity of the quality characteristic (dexterity) to each design factor and interaction, the contribution of each factor/interaction to the data variance is calculated and compared to the total data variance. This is effectively done by calculating the sums-of-squares (SS) of each factor/interaction and comparing them to the total SS. The total SS about the mean for our data is calculated as follows:

$$SS_T = \Sigma\Sigma y^2 - (\Sigma\Sigma y)^2/N$$

where y = average response for each trial
N = total number of data

Since we are analyzing data for three noise (shoulder roll angle Ø) levels, there are three SS_T values to be calculated:

For Ø = 0°, SS_T = 143180.64 - (829556.64)/8 = **39486.06**

For Ø = 5°, SS_T = 143957.6 - (845664.16)/8 = **38249.58**

For Ø = 15°, SS_T = 120109.68 - (711660.96)/8 = **31152.06**

To determine the significance of the data variation for each design factor and interaction, the individual SS's and their percent contribution to the total variation were calculated. The calculations for the individual factor/interaction SS's are as follows:

$$SS_{F_i} = [(F1)^2/n1 + (F2)^2/n2 + ... + (Fi)^2/n_i] - (\Sigma\Sigma y)^2/N$$

where F_i is the design factor/interaction, and
n_i are the number of data points associated with each factor/interaction

Once again, to ascertain the effects of the noise factor these values were calculated for each noise level.

For Ø = 0°:
SS_{wl} = (43681) + (60712) - (829556.64/8) = **699.38**
SS_{jl} = (97094.56) + (20678.44) - (829556.64/8) = **14078.42**
$SS_{wl \times jl}$ = (48664.36) + (55131.04) - (829556.64/8) = **100.82**
SS_{wjd} = (45667.69) + (58418.89) - (829556.64/8) = **392**
$SS_{wl \times wjd}$ = (45496.89) + (58612.41) - (829556.64/8) = **414.7**
$SS_{jl \times wjd}$ = (49862.89) + (53870.41) - (829556.64/8) = **38.72**
SS_{lr} = (14089.69) + (113366.89) - (829556.64/8) = **23762**

For Ø = 5°:
SS_{wl} = (52854.01) + (52854.01) - (829556.64/8) = **0.0**
SS_{jl} = (101314.89) + (20022.25) - (829556.64/8) = **15629.12**
$SS_{wl \times jl}$ = (52624.36) + (53084.16) - (829556.64/8) = **0.5**
SS_{wjd} = (50760.09) + (54990.25) - (829556.64/8) = **42.32**
$SS_{wl \times wjd}$ = (48488.04) + (57408.16) - (829556.64/8) = **188.2**
$SS_{jl \times wjd}$ = (58177.44) + (47785.96) - (829556.64/8) = **255.38**
SS_{lr} = (15550.09) + (112292.01) - (829556.64/8) = **22134.08**

For Ø = 15°:
SS_{wl} = (46139.04) + (42849) - (829556.64/8) = **30.42**
SS_{jl} = (87143.04) + (16027.56) - (829556.64/8) = **14212.98**
$SS_{wl \times jl}$ = (42025) + (47002.24) - (829556.64/8) = **69.62**
SS_{wjd} = (45496.89) + (43472.25) - (829556.64/8) = **11.52**
$SS_{wl \times wjd}$ = (43139.29) + (45838.81) - (829556.64/8) = **20.48**
$SS_{jl \times wjd}$ = (46010.25) + (42973.29) - (829556.64/8) = **25.92**
SS_{lr} = (14232.49) + (91506.25) - (829556.64/8) = **16781.12**

Since these were purely kinematic simulations with no sources of error, the trials were not repeated, hence there is no repetition error involved. Therefore, the variations given for the factors and interactions represent the total data variation present. This also means that all the information from the experimental results is accounted for in the factors and interactions.

The percent contribution of each factor/interaction to the total data variance, given in Table 4, is calculated by simply ratioing the factor/interaction SS's with the SS_T.

Noise Level	Wrist Length	**Joint Limits**	wl x jl interact	Wrist Design	wl x wd interact	jl x wjd interact	**P/O Ratio**
Ø = 0°	1.77	**35.65**	0.26	0.99	1.05	0.10	**60.18**
Ø = 5°	0.00	**40.86**	0.00	0.11	0.49	0.67	**57.87**
Ø = 15°	0.10	**45.62**	0.22	0.04	0.07	0.08	**53.87**

Table 4 Percent Contribution of Factors & Interactions to Total Data Variance

The Table 4 results show quantitatively what the raw experimental results of Section 5.0 show graphically - that the only factors or interactions with significant contribution to data variance are Wrist Joint Limits and Positioning/Orienting Link Length Ratio. These composite percentage results are also shown graphically in bar-chart form in Figure 8.

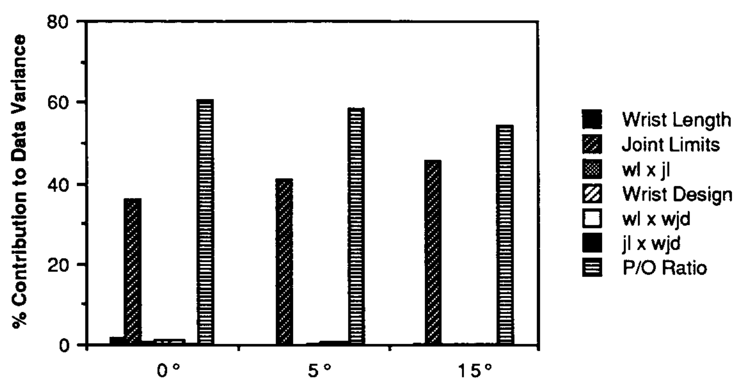

Figure 8 Factor Contributions to Total Data Variance for each Noise Level Value

8.0 Confirmation Trial

A confirmation trial was run with a manipulator configuration that uses the best joint limits and positioning/orienting link ratio, but leaves the other factors at the current FTS manipulator baseline design. In other words, this configuration uses shoulder pitch joint limits of +180°/-90°, a 16" distributed actuator wrist with ±120° pitch and yaw joint limits, and has upper arm and forearm link lengths of 51.5". Since the noise source had an insignificant effect on data variation relative to the design factor levels, this trial was performed in the 0° shoulder roll position only, using the same workspace points as configuration #5.

The results of this trial indicate an average orientation angle of 220.8°, which is insignificantly lower than the best scoring configuration - configuration #5 (concurrent axis wrist) - as would be expected.

8.0 Summary and Conclusions

These experimental results point to two potential manipulator modifications which would yield significant gains in dexterous capability for the SSSFD program: (1) increasing the FTS manipulator shoulder pitch joint limits to +180°/-90° and wrist pitch and yaw limits from ±90° to ±120°, and (2) increasing the positioning-to-orienting link length ratio as much as feasible. They also indicate that - within a range allowing reach to the workspace points - the shoulder roll joint position has an insignificant effect on dexterity.

Of these two factors, the link ratio has a slightly higher performance yield if taken from 2:1 to the 7:1 level, however, it also involves significant impacts to weight, stiffness, power consumption, thermal control, and stowed volume, especially if tip force and control input bandwidth performance is to be maintained. In addition, a preliminary experiment which varied the link ratio from 5:1 to 9:1 showed insignificant impact to dexterity, indicating a function which rises rapidly above 2:1 and levels off somewhere prior to 5:1. This factor should be investigated in more levels between 2:1 and 5:1.

The joint travel limit factor - although not a trivial design issue - is probably the best candidate for modification to improve dexterity.

REFERENCES

1.Gupta, K. C., "On the Nature of Robot Workspaces," International Journal of Robotics Research, Vol. V, No. 2, 1986

2.Ross, Phillip J., *Taguchi Techniques for Quality Engineering*, McGraw-Hill Book Company, 1988

3.Terninko, John, *Introduction to Quality Engineering Using the Philosophy of Dr. Genichi Taguchi*, Responsible Management, Durham, N. H.,1989