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Design of a Hexapod Motion Cueing System for the NASA Ames Vertical Motion Simulator

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Abstract

NASA at Ames Research Center operates the world's largest motion-base flight simulator, the Vertical Motion Simulator. This simulation facility supports a wide variety of research by allowing flexibility in both hardware and software. As part of a VMS Modernization Plan, NASA Ames elected to consider major alterations to the motion-base configuration. One of these was the incorporation of a hexapod on the lateral carriage of the vertical beam. This would replace both the longitudinal carriage (that provides ±4 feet of surge) as well as the rotational gimbal (that simultaneously provides ±18 degrees pitch, ±18 degrees roll, and ±24 degrees yaw). However, standard off-the-shelf hexapod geometries did not meet the requirement for this large simultaneous motion capability. New geometric designs were created based on optimization of the geometry to maximize workspace and flight metrics.

This paper describes the development and implementation of these optimization and evaluation metrics. Design solutions are explored from workspace and simulation fidelity perspectives. Kinematic design issues of the hexapod are presented, including the trade-offs necessary to ensure high performance within a safe operational environment. Integration of the design with the VMS presented its own challenges, and the most relevant of these are also presented.

1 Background/Introduction

The Vertical Motion Simulator (VMS) at NASA Ames Research Center has been in operation since the mid 1970's. The VMS is a one-of-a-kind simulation research and development facility. It offers unparalleled capabilities for conducting experiments involving some of the most challenging

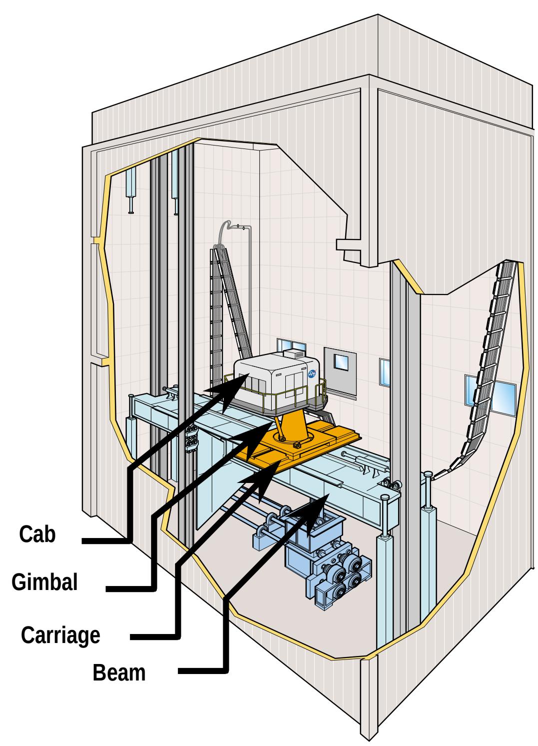

Figure 1 – Current VMS motion system, showing three-axis gimbal mounted on carriages and beam.

aerospace disciplines. The VMS, shown in Figure 1, is a very large, six-degrees-of-freedom electro-mechanical/electro-hydraulic servo system. It is located in and partially supported by a specially-constructed 73-foot-wide by 36-foot-deep by 120-foot-high tower, whose entire interior volume is available for the operation of the motion system. The motion platform consists of a 40-foot long beam, which can travel up to ±30 feet vertically. On top of the beam is the lateral carriage that traverses the 40-foot length of the beam. Then, on top of the carriage is a longitudinal carriage and gimbal system that can simultaneously provide ±4 feet longitudinal, ±18 degrees pitch, ±18 degrees roll, and ±24 degrees yaw.

In addition to its size, another unique feature of this facility is that it can simulate the physical cueing environment of a large range of vehicles. Five cabs representing the cockpits of a variety of vehicles - each with its own instruments, controls, visual display and audio cueing systems - can be placed on the motion cueing system of the VMS.

In continuous efforts to keep the VMS performance on par with increasingly demanding research requirements and regulatory standards, NASA Ames elected to consider several major alterations to further improve its existing motion-base configuration. One of these was the incorporation of a hexapod in place of the gimbal system on the lateral carriage of the vertical beam. This would ideally result in a system either matching or improving on the current performance charted in Table 1 (*simultaneous* capabilities of generating displacement in surge, and rotation in pitch, roll, and yaw).

***Table 1** – VMS Nominal Operational Limits*

Axis	Displacement	Velocity	Acceleration
Vertical	± 30	16	24
Lateral	± 20	8	16
Longitudinal	± 4	4	10
Roll	± 18	40	115
Pitch	± 18	40	115
Yaw	± 24	46	115
All numbers, units ft., deg., sec.			

What made this effort challenging, however, was to take advantage of the beneficial nature of hexapod mechanisms, while overcoming their inherent simultaneous axis displacement limitations.

1.1 Motivation for An Optimized Hexapod Configuration

Before electing to incorporate a hexapod into the VMS, performance enhancements to the existing gimbaled system were investigated and found to be quite expensive due to the unique one-of-a-kind nature of this system. Further investigation found readily-available complete turnkey hexapod motion systems comparable in cost to the originally-proposed gimbal actuator modifications.

While potential cost savings instigated an investigation into modern day hexapod technology, it quickly became apparent that standard hexapods could not meet the VMS simultaneous-axis performance requirements in table 1. This is because a hexapod generates its motion by simultaneously extending and/or retracting its six legs, and generates the greatest displacement in any axis when it is only moving in that particular axis. For example, if a hexapod is capable of generating ±25 degrees in roll and the system is at its maximum 25-degree roll displacement, two of its six actuators would be fully extended, two would be completely retracted, and the remaining two actuators would me somewhere at their mid-stroke position.

If displacement from any other axis is commanded, the system must first reduce its 25-degree roll displacement to “free up” actuator stroke for use by the other axis. An exception would be if the axis commanded used only the actuators that were at mid-stroke.

Accordingly, as additional axes are simultaneously commanded, the displacement capability of the hexapod becomes increasingly limited. Performance is also taxed by simultaneous axis commands because oil flow requirements increase during simultaneous actuator displacements. Typically, a hexapod is symmetrical because symmetrical geometry allows maximum displacement in all axes, which is desirable if the hexapod is the only source of motion.

While increased displacement in any specific axis can be achieved by altering the geometry of a symmetrical mechanism, it will be at the expense of displacement in other axes.

1.2 Hexapod Performance Objectives

An initial hexapod investigation focused on the replacement of only the rotational capabilities of the gimbal system currently mounted on the VMS longitudinal carriage. This hexapod would have simultaneously provided ±18, ±15 and ±20 degrees in pitch, roll and yaw, respectively. This envelope was thought to be sufficient for the range of anticipated VMS experiments. Nonetheless, there were a few potential difficulties with this solution: Combined motions of the hexapod and the longitudinal table could have led to cab-wall interference, and the complexity of the entire system would have increased. It then became apparent with the optimization tools developed, that the hexapod may be able to provide the required longitudinal motion as well as the rotational motion thereby eliminating the need for the longitudinal carriage. This potentially reduced system cost and mass.

This paper will now explain the approach developed to analyze a motion system's ability to reproduce particular one-to-one aircraft motion cues, and the hexapod geometry optimization process used to tailor a motion system to maximize this cueing capability in the given building volumetric enclosure. Ultimately, the effort concentrated on a solution requiring four degrees of freedom from a hexapod (roll, pitch, yaw and longitudinal motion), with the VMS providing the other two vertical and lateral axes. The final design is a viable replacement candidate for the gimbal and longitudinal system currently on the VMS. Figure 2 depicts the resultant design from application of these tools as applied to a Bosch-Rexroth Corporation hexapod.

Typically, motion system performance is described in terms of single-axis displacement, velocity, and acceleration. The method for defining VMS performance was commonly through maximum axis limit tables like Table 1, which imply axes independence.

Maximum axis limit tables cannot be developed for hexapods because the nonlinear character of hexapods prevents the parallel application of equivalent tables for hexapods. Therefore, a more thorough and complete comparison method was needed before a valid comparison could be made between the gimbaled carriage and hexapod mechanisms. The comparison took the form of two metrics. The first metric focuses on the performance of the machine with respect to the desired quality of its flight simulation, and will be referred to herein as the "flight metric". The second metric focuses on a motion envelope, referred to herein as the "workspace metric".

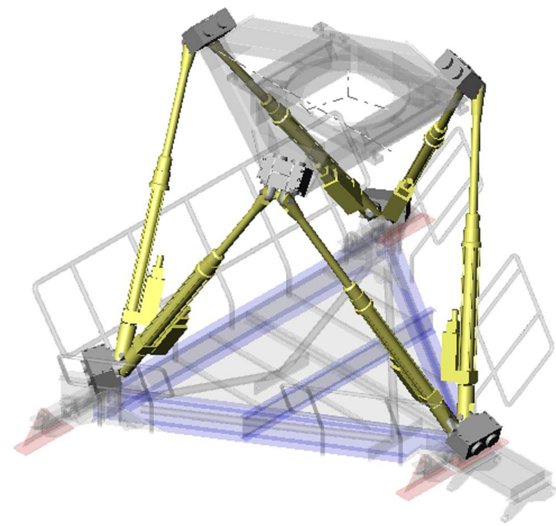

Figure 2 *– Custom-tailored hexapod developed by this program for the VMS, designed to allow replacement of both the rotational gimbal and longitudinal carriage.*

2 Optimization of a Hexapod For Flight Simulation Performance

2.1 Definition of Flight Metric

The flight metric was developed on the basis of tuning practices employed prior to each simulation. The objective of tuning is to reduce the flight envelope (true aircraft motion cues) to fit the physical limitations of the simulator workspace while retaining as much flight quality, in terms of fidelity, as possible. Chung[2] & Schroeder[3] further define and detail mathematics and techniques for tuning motion simulator systems.

Reducing the motion envelope involves several parameters referred to as gains. Motion algorithm gain amplitudes are used to control how closely the simulation achieves the motion cues that the actual aircraft is expected to deliver. Typically, reducing a gain reduces some aspect of the motion envelope, making it then more likely that the given flight simulator's mechanism can accomplish the motion. As the motion envelope is reduced, fidelity is correspondingly eroded as the motion cues lose amplitude, shape, and phase.

The tuning process is interactive and involves subjective responses from the pilot making it difficult to forecast the resulting motion quality for a simulator design not yet built. To enable answers regarding flight fidelity for that situation, the flight metric method attempts to extrapolate by using two steps.

In the first step, aircraft model output data is captured during a simulation. This data is then run through motion algorithms tuned to provide the maximum motion reductions still allowing high-fidelity[4] motion (in which the motion sensations are not noticeably different from those of actual flight). At this point, the data reflects pilot, aircraft model, and researcher tuning practices, but is not tailored (limited) to run on (or fit within the motion capabilities of) a specific simulator mechanism.

The second step multiplies the data by a single reducing factor, which can be thought of as a spherical gain, since it is applied uniformly to all axes of motion. This gain therefore is a flight metric in terms of simulation fidelity, with a gain of 1.0 implying flight quality inside the 'high-fidelity' zone, rather than 1:1 flight cues. As this is decreased below 1.0, the simulation fidelity is correspondingly decreased. The gain value of interest is the maximum a proposed mechanism can achieve.

2.2 Calculation of the Flight Metric.

The flight metric of a candidate design is calculated by using a set of high fidelity flight simulation motion files and an emulator. The motion data set was selected to reflect past, current, and future simulations at AMES. The emulator first assembles the simulator design by taking a geometric description of the VMS with or without a hexapod, and a set of constraints as additional inputs. It then reads motion data, translates them into actuator space commands by using vector algebra with rotation matrices, indicates where the actuators have the least available performance remaining, and lists occurrences where they would exceed their physical extension or retraction limits. The simulation parameters are automatically re-tuned with enhanced maneuver anticipation (an experimental fidelity enhancement method developed in-house at AMES) to maximize, in our case, the gain while barely eliminating those occurrences. The emulator was 'flown' for each generated geometry, solving for whichever displacement, velocity, or acceleration limit would occur first in any of the actuators.

The reported gain is thus limited to the highest value manageable by the machine. Gain values over 1.0 do not imply a noticeably better simulation, so the estimated gain achievable for each flight is truncated down to 1.0 before averaging over all flight profiles of interest. The result is the highest average overall estimated simulation fidelity achievable for those simulations running on a proposed simulator design. By calculating the flight metric of every promising design, eventually the optimum design can be identified based on superior matching of simulator motion capabilities to specific simulations.

2.3 Flight Metric Geometry Optimization Loop

The geometry optimization loop is presented in Figure 3, and is achieved by using the flight metric calculation (in our example a simulation (sim) gain estimator) as a filter applied to a set or family of possible hexapod designs. A family of designs is a set of hexapod geometries each using the same actuator dimensions. An infinite number of different hexapod designs is still possible given six gimbal points in three dimensions. The term "Hexapod Geometry Generator" refers to any

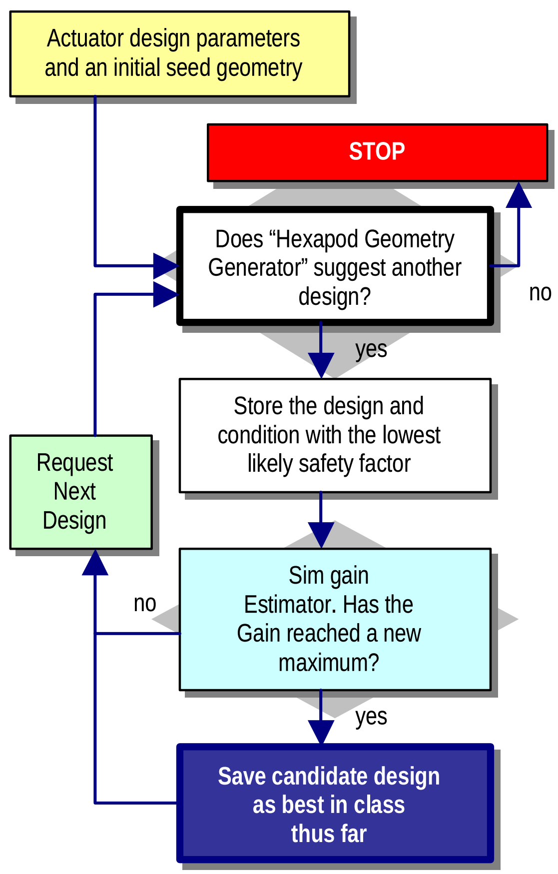

***Figure 3** – Geometry Optimization Loop*

systematic way of producing a family of designs with varied gimbal locations for subsequent evaluation. The necessary characteristics of this generator are the ability to export at least one complete hexapod geometric description, and an automatic termination of production. Such termination ensures there is a stopping point when either negligible improvement is seen in any performance metric (during continued rearrangement of the gimbals), or the family of design possibilities embodying the common theme is to a level of sufficient resolution exhausted. When a complete family of designs has been generated, tested and emulated, only the highest rated, by flight metric, are retained.

This design process was initially carried out manually by generating one design at a time. Eventually path-searching routines were developed to read constraint data and compute the directions in three dimensions that two gimbal points at a time could be moved for maximum gain improvement. Automatic termination occurred when successive results showed improvements less than 0.1% per inch of gimbal movement.

2.4 Multidisciplinary Aspects

Higher levels of optimization involve actuator design, structural, and other effects. These are summarized in the flowchart of Figure 4, which illustrates how an overall design is made which reflects optimal choices in actuator design, structural arrangement, cost, safety factor, and hexapod geometry. Since most calculation occurs in the geometry optimization, use is made of parallel batch computing means to get faster results.

A typical complete off-the-shelf (COTS) hexapod was selected as an initial design and run through the geometry loop once. Its "gain" performance estimate of 0.55 substantially trailed that of the gimbaled VMS. After the multidisciplinary evaluation (Figure 4), the next iteration incorporated modifications to both the actuators and gimbal locations. Another pass through the geometry optimization loop indicated gain estimates were higher, as hoped. This marked the first complete iteration. At this point, a benchmark design existed with performance numbers that could still be improved upon.

Early results are tabulated in Table 2. As expected the higher displacement capability of the VMS results in a significantly higher gain than that of a COTS hexapod. When the hexapod is merged with the VMS and evolved, estimated gains theoretically surpass the VMS value. None of these designs can match the

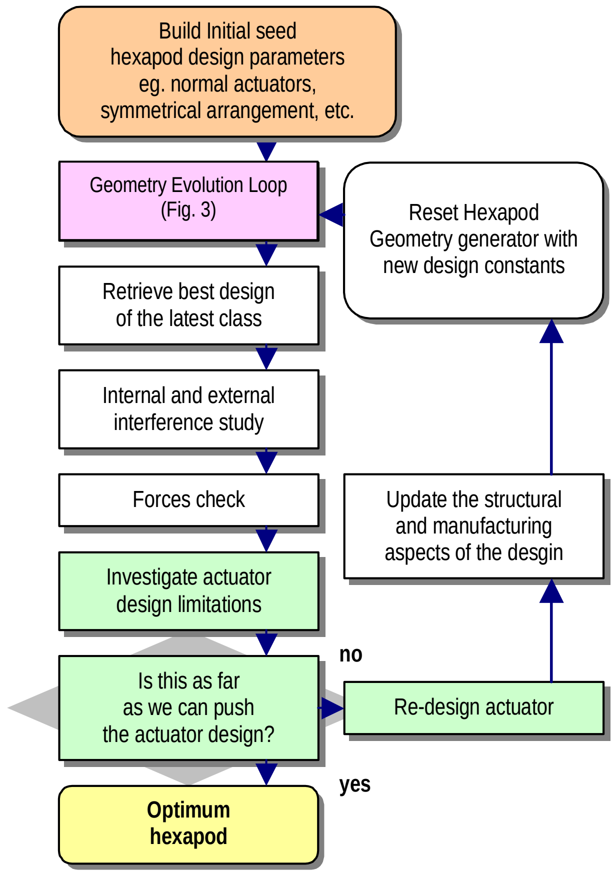

Figure 4 *– Overall multidisciplinary optimization method for the VMS hexapod design*

simultaneous excursion limits of the VMS. Nevertheless, the conclusion is that with a suitably designed complementary hexapod mechanism, the VMS has the potential to achieve very high performance despite reduced simultaneous excursion limits.

Table 2 *- Estimated Performance Improvement.*

Configuration	Estimated 6-Axis Gain
Current VMS Motion System	0.66
COTS hexapod	0.13
COTS hexapod on VMS	0.55
Design Iteration A on VMS	0.72
Design Iteration B on VMS	0.74

3 Hexapod Workspace Kinematic Optimization Problem

The core of this design effort was the generation of a viable hexapod design that would meet the desired performance workspace objectives. These objectives were given in Table 1. While the hexapod would only be required to generate the rotations and the longitudinal motion, these would have to be generated simultaneously, which meant applying a systematic approach to the design of the hexapod.

A process developed by Advani[8, 9] for the optimization of hexapods with respect to a specific design objective was the starting point for this analysis. The fundamentals will now be explained.

3.1 Workspace of hexapods

The main objective of a mechanism is to impart motion to the end-effector "***C***" over a specified range of positions and orientations. In motion-bases, the end-effector is usually the moving-platform reference point, typically the geometric centre of the upper platform gimbal joints (see Figure 5).

The "workspace" is defined as the totality of points that this end-effector can achieve, and is a six-dimensional volume describing the maximum excursions and rotations of ***C***. Determination of the workspace requires (a) a description of the mechanism, and (b) knowledge of the *ranges* of the joint variables.

Many methods have been proposed for the determination of robotic workspace[10, 11, 12]. Particularly in the case of parallel mechanisms, this is not a trivial task. The method developed by Haeck[13], which solves for the workspace boundary in solution space using ray-tracing methods, was applied in this investigation due to its accuracy and its suitability for the subsequent optimization problem.

The physical interpretation of the six-dimensional workspace is not straightforward, mainly since the angular limits, while having real and finite values, are difficult to interpret physically. An objective function may be used and the actual fitting of a particular mechanism to that function will yield a single quantity. For general motion-cueing systems, an elliptical objective function was developed[1]; however, since we were interested in the combined extreme motions of the hexapod in this analysis, a cubical function was developed. It simply compares the actual workspace (quantified in metres and degrees) of a given hexapod geometry to the volume of a six-dimensional cube having the dimensions of the required simultaneous motions (Table 1).

In order to tailor the mechanism such as to yield the highest possible workspace objective, the geometry must be altered and the allowable range of physical parameters defined. From a practical point-of-view, this is by no means a random task. Certain geometric variables will have a greater impact than others. Furthermore, the mechanism must always remain stable.

Hexapods with specific workspace capabilities can be found in public-domain literature [5, 14].

3.2 Hexapod geometry

Hexapod-type motion-base mechanisms (also referred to as Stewart Platforms) are usually comprised of a base-frame, six prismatic actuator legs (the jacks), and an upper moving platform that carries the payload. The legs are attached in pairs, via gimbal joints, to the upper and lower platforms near the vertices of their respective frames. All of these elements have kinematic and other

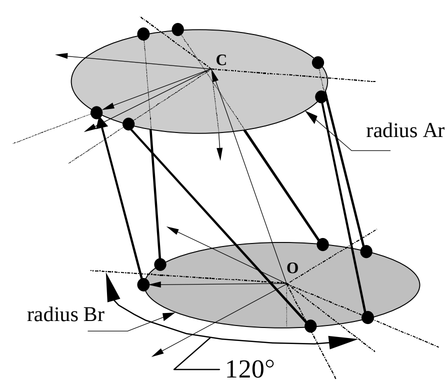

Figure 5 *- Kinematic representation of the typical circular layout of a symmetric hexapod mechanism*

properties that must be taken into account when modifying the design. For instance, the gimbals have allowable excursion ranges, load limits, and mechanical interface requirements.

The motion of the six legs of a hexapod is constrained by their minimum and maximum lengths. The maximum length of this type of actuator is limited by the decrease of stiffness with greater length, and the ability of manufacturing technologies to produce long cylinders that are suitable for hydrostatic bearing applications. In order to prevent excessive forces during runaways, the actuators are equipped with safety buffers, which help decelerate the piston before it reaches the end of the cylinder. From a kinematic point-of-view, the buffer reduces the effective operational stroke available for normal motion.

Although the workspace is a function of all of the above kinematic parameters, and each of these parameters limited by manufacturing and materials technologies, the designer must also ensure the mechanism is well conditioned. This means that it should behave deterministically and is controllable at all times.

3.3 Mechanism conditioning

The mechanism must possess a specified level of stability or "conditioning" throughout its workspace, meaning that its kinematics equations do not become singular, and the mechanism remains reasonably *distant* from these singularities[16]. The conditioning of the mechanism varies as a function of the configuration itself, and the instantaneous pose (position and orientation) within the workspace. A well-conditioned platform is easy to control, provides high positioning accuracy and does not contain any singularities within its workspace.

Conditioning can be mathematically described through the Jacobian matrix, which maps the rates of a specific point on the moving platform (usually the kinematic centroid of its gimbals), to the rates of the actuators. Hence, in a well-conditioned platform, motion of the actuators will lead to a relatively small motion of the platform. In a poorly-conditioned system, small motions of the actuators will result in large motions of the platform.

A mathematical term, commonly used in the field of robotics to express the conditioning (poor condition implies proximity to a singularity) is referred to as *dexterity*. It is defined as the inverse of the condition number, which is the ratio of the lowest to the highest singular values of the Jacobian matrix. The dexterity,

like the Jacobian matrix, varies throughout the workspace, and the *minimum* dexterity - the lowest value achieved at any point in the (nonlinear) workspace - must be constrained [17].

An analysis of several commercial off-the-shelf flight simulator motion-bases showed that a minimum dexterity value of 0.2 is common, and would be a reasonable starting point for the optimization. If the ensuing loads analysis would demonstrate difficulties in specific corners of the workspace, the design may then be altered.

4 Geometry for Workspace Optimization

When specifying the geometry of a hexapod, one is free to choose the geometry. Therefore, one can specify in three-dimensional space the locations of each upper and lower leg attachment point, as well as the properties of each leg, all of which influence the resulting workspace of the motion base.

4.1 Geometric parameters

In this design study, a standard, proven COTS system was used as the starting geometry. The workspace was progressively tailored by varying the geometry itself and gradually introducing more parameters. The geometry was varied by re-locating and re-orienting the gimbal blocks, and by determining the optimal stroke-length of the actuators.

In Figure 6, the geometric parameters of a generalized base platform and upper platform respectively are given. The gimbals are arranged in pairs on the upper and lower platform as in conventional hexapod motion-bases. In this case, they are located on *two* concentric circles, rather than one. The outer pairs on the upper (or lower) platforms are located from the Y-axis by angle

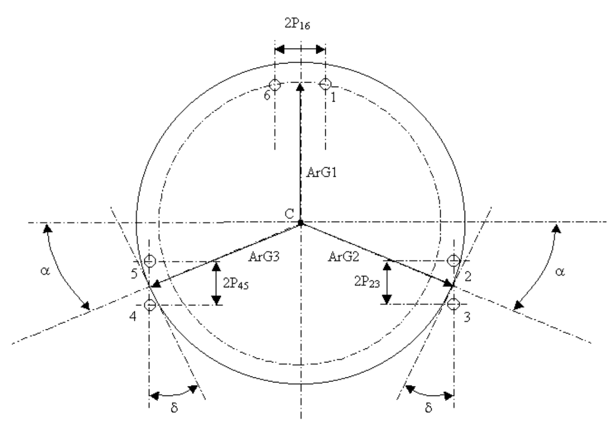

Figure 6 *– Layout of the generalized double-concentric hexapod platform. Note that the two circles may be non-coplanar.*

Alpha and can be independently skewed non-tangentially by angle Delta. On the upper platform, the gimbals are all located on a single plane, while on the lower platform, the forward gimbals (given here by numbers 1 and 6) may be situated higher or lower than the other four.

The suppliers of motion cueing systems typically provide actuators with standard (and somewhat arbitrarily determined) stroke lengths; e.g. 60 inches. It is, however, relatively inexpensive to change the cut length of the cylinder and piston rod of the actuator without influencing the design (or size) of its other "dead-length" components, like the cylinder end blocks, attachment clevises, or the hydraulic manifold blocks.

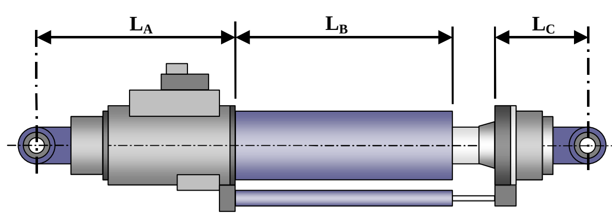

***Figure 7** - Fixed and variable kinematic design parameters typical of the linear servomotors used in hexapod motion-bases.*

A given range of cylinder/rod lengths can be specified by the manufacturer, and the cylinders cut accordingly. The sum of the axial dimensions of the fixed-length components (L_A + L_C in Figure 7) is called the dead length, and does not change.

On the other hand, the designer can allow the "cut length" of the actuator cylinder and piston rods to be determined by the optimization, rather than arbitrarily.

This flexible approach enables the designer to specify a system that extends or "stretches" its envelope in specific degrees-of-freedom. The challenge is to design an optimization method that allows this tailoring to take place, while taking into account the design constraints.

4.2 Optimization routine

An optimization technique utilizing a *Linearly-Constrained Quadratic Programming* sub-problem with inequality constraints was developed. Like most optimization methods reported in literature, this iterative technique minimizes an objective function while remaining within two constraints. These are the *minimum* dexterity of the platform, and the geometry of each member in the mechanism. While the locations of the gimbals and the stroke length of the actuators may vary, these variations must remain within constrained bounds.

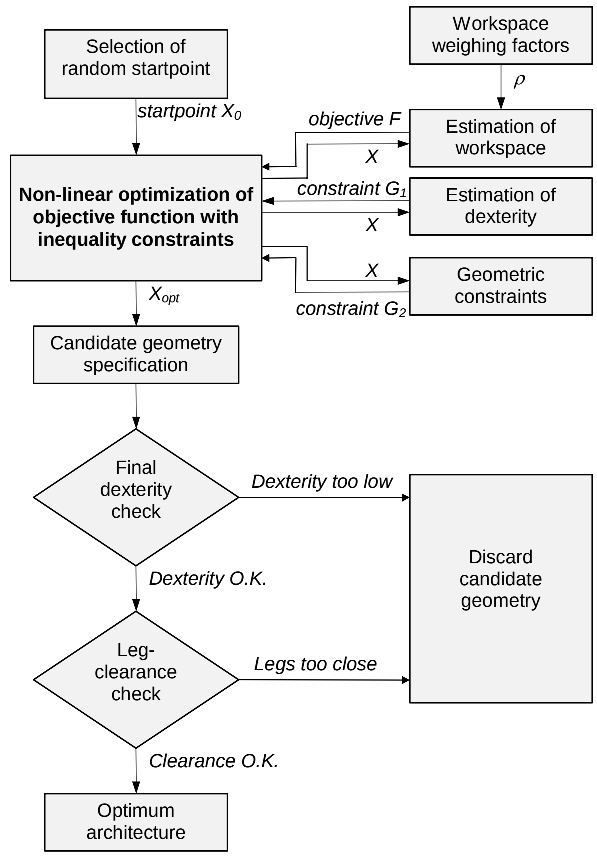

***Figure 8** – Hexapod mechanism optimization technique (Advani 1998)*

At each step, the new solution is checked against the optimality conditions for the true problem to determine whether another step must be taken. The optimization is schematically shown in Figure 8, and is the most inner of the optimization loops of the process described in this paper.

4.3 Results

Figure 9 shows the workspace of the mechanism prior to the optimization. This is representative of a standard hydraulic system with a 60-inch operational stroke. Note that the rectangular box represents the desired simultaneous motion cueing capability of the system, as specified by NASA. The contours represent roll motion limits in increments of 5 degrees.

The workspace of the optimized system is shown in Figure 10. The stroke was increased by only 4.74 inches beyond the original 60-inches available, and no other non-standard variations to the mechanical system were necessary.

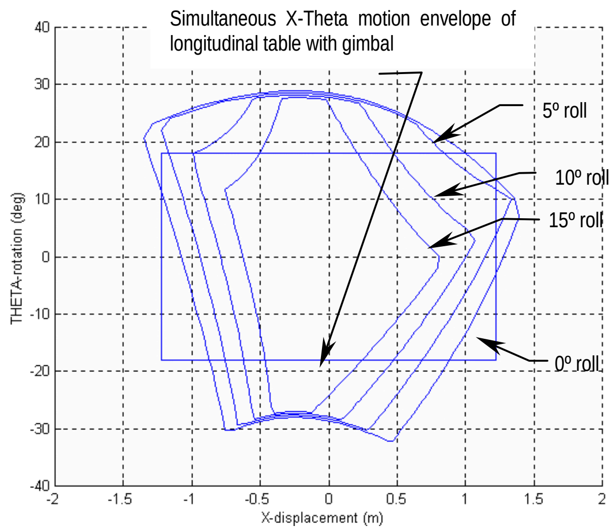

Figure 9 *- Workspace of a conventional off-the-shelf hexapod with a 60-inch actuator stroke. X and Theta workspace is shown, with contours depicting simultaneous roll motions. Box indicates minimum requirement.*

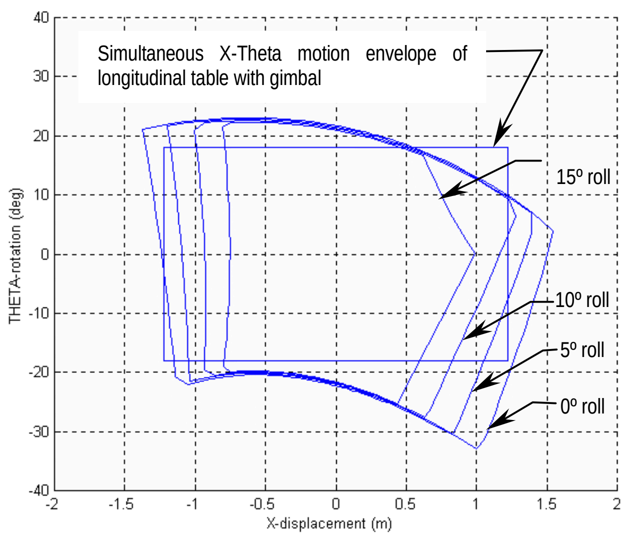

Figure 10 *- Workspace of the hexapod optimized to the objective function through geometric variations of the upper and lower platforms (Fig. 6), and the actuator lengths (Fig. 7).*

The ratio of the required objective function to the workspace increased from 0.64 to 0.769, indicating an average relative improvement of 20.1 percent for each degree-of-freedom. This represents a *volumetric* improvement of 1.734.

Three-dimensional volumes of the X, Phi and Theta motion envelopes, before and after the optimization, are plotted in Figure 11. The rectangular solid depicts the optimization objective, defined by the simultaneous motion envelope of the current longitudinal carriage and gimbal system.

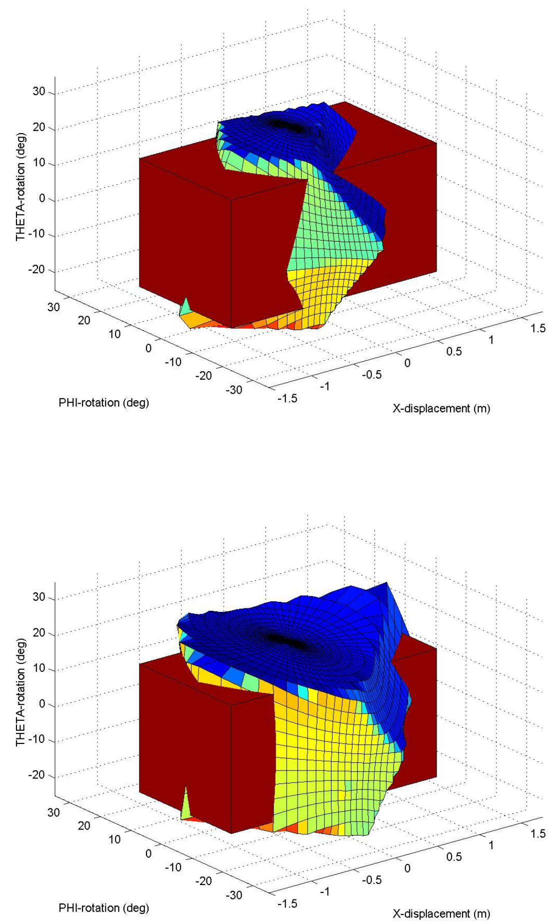

Figure 11 *– Three-dimensional illustrations of workspace of standard off-the-shelf 60-inch hexapod (above), and optimized VMS system (below). Red box indicates desired simultaneous motions, those which can be achieved by the current gimbaled system.*

5 CONCLUSIONS

This project established that a hexapod is a viable replacement candidate for the gimbaled system currently on the VMS.

The systematic processes and tools developed for this project provide a thorough yet fast method for developing custom motion simulators through minor alterations of a common off-the-shelf hexapod.

The salient conclusions are as follows:

- The tools generated numerous designs that afford the opportunity to make cost, performance, off-the-shelf selection, etc., design trade off decisions. This flexibility is extremely attractive as it provides the engineer to tailor a system giving priority or weight to those factors most important to the customer.
- The optimization operates on a large number of design variables and, hence, has a large number of local minima that appear close to the global minimum. This allows the designer to select from not only the best mathematical optimum, but nearly as well-performing solutions that may even offer advantages from a manufacturing or integration point-of-view.
- The original assumption that the minimum allowable dexterity be no lower than 0.20 was valid. Subsequent dynamics analyses confirmed that, in the optimized geometric solution, the forces in the hexapod would always remain within acceptable bounds.
- The designer must choose carefully the number of design variables, and the geometric constraints allowed on the system. This must be performed in concert with the manufacturer in order that realistic and cost-effective trade-offs can be made.
- The hexapod may not always achieve the simultaneous motion capability as, for example, the gimbaled system (as was illustrated in Figures 9, 10 and 11). In this particular design example, the optimized hexapod is tasked with large longitudinal motions and all three rotations. The solution provides significantly greater absolute single-degree-of-freedom motion capability.
- The designer must carefully choose which design variables to optimize for a particular simulation objective.
- Workspace is not the only criteria by which to measure or compare the performance of a hexapod. This methodology, however, allows the end user to benefit from the advantages of hexapod solutions - stiff, compact and cost-effective - with the maximum achievable capability from that device.

Final Note:

The methodology, tools and processes developed in this program are mature, tested and ready for application in other hexapod design problems, for simulation, or any relevant application.

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