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Don't Touch! Using the NISER Method to Avoid Reaching the Space Envelope Limits of a Hexapod System

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The main objective of any motion cueing algorithm is to represent the acceleration of a simulated aircraft as good as possible. The main constraint is the space envelope the motion system is able to reach. Reaching this limit inevitably leads to a sudden change of the current movement and the pilot faces an unexpected and therefore disturbing acceleration. As a consequence, any cueing algorithm has to be parametrized in a way to prevent the motion system from touching the limits of the usable space. If, for any reason, this is not possible e. g. due to inadequate pilot actions or unforeseen simulator operations a strategy to avoid false cues as good as possible needs to be implemented. This implies that the limits are known. Unfortunately, calculating the platform position by using a set of actuator lengths for a parallel robotic system like a hexapod motion ends up in an iterative process. Therefore, most current limiting functions refer to the actuator states to decide whether the platform is approaching a limit or not. The problem with this method is that reaching the limit of an actuator does not imply which degrees of freedom of the entire system are affected. In some cases, it is even not possible to decide which direction of a degree of freedom needs to be limited. In order to tackle this deficiency this paper proposes a non-iterative method to calculate the current space limits for all six degrees of freedom using the current platform position and the lengths of the fully extended and retracted actuators. Based on this information it is possible to restrict the movement of the motion in the affected degree of freedom in case the platform approaches a limit. Two limiting functions, one for translational and one for rotational degrees of freedom are given. Finally, the effectiveness of the proposed limiting functions is demonstrated for a rejected take-off run due to an engine failure before the decision speed V_1. This is both, a common and an aggressive maneuver for aircraft training simulators.

I. Nomenclature

$Act.$	Actuator
APK	Advanced Platform Kinematics
$AVES$	Air Vehicle Simulator
AVF	Apparent Vertical Filter
CWA	Classical Washout Filter Algorithm
D	Number of degrees of freedom of a robotic system
dof	Degree of freedom
$f_{aa,x,in}$	Specific force in longitudinal direction MDA input signal
$f_{aa,x,out}$	Specific force in longitudinal direction MDA output signal
$f_{aa,x,out,lim}$	Specific force in longitudinal direction MDA limited output signal
$f_{aa,y,in}$	Specific force in lateral direction MDA input signal
$f_{aa,y,out}$	Specific force in lateral direction MDA output signal
$f_{aa,y,out,lim}$	Specific force in lateral direction MDA limited output signal
L	Number of blocked degrees of freedom in a robotic system
MDA	Motion Drive Algorithm
N	Number of elements of a robotic system

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$NISER$	Non-Iterative Space Envelope Recalculation method
V_1	Decision speed during take-off maneuver
r_{max}	Maximum length of motion system actuator
r_{min}	Minimum length of motion system actuator
x_g	Longitudinal position in inertial coordinate system
$x_{limited}$	Limited commanded position of motion system in surge
$x_{unlimited}$	Unlimited commanded position of motion system in surge
z_g	Vertical position in inertial coordinate system
Θ	Pitch angle of motion system
$\varphi_{limited}$	Limited commanded roll angle of motion system
$\varphi_{unlimited}$	Unlimited commanded roll angle of motion system

II. Introduction

More than ninety years after Edwin A. Link invented the "Pilot Maker" [1, 2] the challenge to supply pilots with the best possible motion cues in a training simulator still remains. Thus, it is not surprising that the pros and cons of motion cues are widely discussed because the operating costs they entail [3, 4] need to be justified in an ongoing discussion about the transfer-of-training value of motion systems [5, 6]. Furthermore, pilots still feel interfering forces resulting from the fact that reaction forces, e. g. the centrifugal force during coordinated turns, cannot be replicated due to the limited envelope space that is available for motion systems [7]. Another source of interfering forces are the operational limits of the motion system. A couple of strategies are in use to prevent the motion form reaching its limits. The first and most important measure is a good parametrization of the motion cueing algorithm. A corresponding procedure is e. g. proposed in [8] for a Classical Washout Filter Algorithm (CWA). This is to make sure that for a given set of tasks the accelerations of the simulated aircraft are represented in the best possible way. But "the best possible way" depends on some constraints which are to be met during the entire operation spectrum. In [9, 10] a method is presented to analyze the given space as well as the maneuvers that are expected to be performed during a set of simulator sessions. For a set of precisely defined maneuvers executed with minor deviations, e. g. due to flight guidance support or instructions, these methods are very effective. The main drawback is that because of both, the variety of maneuvers performed in a training simulator due to legal regulations [11] and new training concepts like the Evidence Based Training [12,13] the demand for even more flexibility is increasing. Furthermore, due to training operations, pilots may handle a given situation in an unforeseen way resulting in an even bigger variety in the simulator motion.

As a consequence, more flexible strategies are proposed for current simulators. Examples are the Coordinated Adaptive Washout Algorithm [14] and corresponding adaptive cueing algorithms based on actuator states e. g. presented in [15, 16, 17]. The main idea is that if the state of the motion platform is known, it is possible to manipulate the parameters of the cueing algorithm in a way that the best possible representation of the current maneuver is possible while the space envelope limits are observed. The major drawbacks are on one hand that this approach involves the chance that the same maneuver executed by the same pilot in the same way might result in a different response by the motion due to deviating starting conditions like a different position of the platform at the beginning of the maneuver. This may result in a difficult corrective process because if a pilot complaints for an improvement it is not easy to reproduce the same situation. This is even more true because the structure of such filters tends to be more complex than the structure of a CWA [18, 19]. On the other hand, the limits of the motion system are only known for the actuator states but not for the moving platform. The reason for that is that for parallel robotic structures like hexapod motion systems a desired position of the platform yields for a unique set of six actuator lengths. Vice versa it is not possible to directly calculate the position of the platform using the six actuator lengths only. An iterative method needs to be used as e. g. proposed by [18]. Such an iterative method is either restricted with respect to its accuracy or may result in time frame violations depending on the acceptable position deviation. Using actuator states leads to another disadvantage: The states of an actuator does not inevitably correspond to a rate of change in the platform states. For example, while in heave direction the platform position widely corresponds to an actuator position this is not always the case for surge and sway.

One possibility to mitigate this problem is to use a simpler filter structure like the CWA and add a functionality to avoid reaching the limit of any actuator. One example for this strategy is the Cueing Algorithm used by Moog Company [20] where a cost function is minimized. This functionality is called the Advanced Platform Kinematics (APK) and it manipulates the translational degrees of freedom (dof) only.

This paper proposes an alternative method currently used in the DLR research simulator AVES (Air Vehicle Simulator). It complements the in-house developed Apparent Vertical Filter (AVF), a Motion Drive Algorithm (MDA) given by [23]. During the tuning sessions for a simulator campaign it turned out that without such a function the MDA needs to be much further restricted due to a very small number of aggressive maneuvers. The main idea is that even though it is not possible to directly calculate the position of the platform by using the state of the six actuators it is possible to find the current limits in any dof in case both, the current position of the platform and the actuator limits are known. Furthermore, a method is given where the states of a platform will be limited only if the position is closer to the current space limits than defined by a single parameter for each degree of freedom.

III. The Non-Iterative Space Envelope Recalculation (NISER)

In this chapter the NISER method will be described for an equivalent of a 2D model of a motion system. One way to proof the equivalency is that moving one actuator results in a movement of the upper platform in all cartesian degrees of freedom. This is true for the given example in Fig. 1 below. To be fully equivalent to a 3Dl model the number of dof is expected to be three, one rotational and two translational ones.

According to [21] the number of the dof can be calculated using Grübler's formula for planar mechanisms

$$D = 3(N-1) - L \tag{1}$$

where D represents the number of dof, N the number of elements and L the degrees of freedom blocked by the connecting joints. The number of elements is 8, including the base, the moving platform and three linear actuators each consisting of a cylinder and a rod. Furthermore, there are 6 ball joints and 3 linear joints, each joint blocking 1 degree of freedom. This results in an overall amount of 18 blocked degrees of freedom. As supposed, the number of dof is

$$D = 3(8-1) - 18 = 3 \tag{2}$$

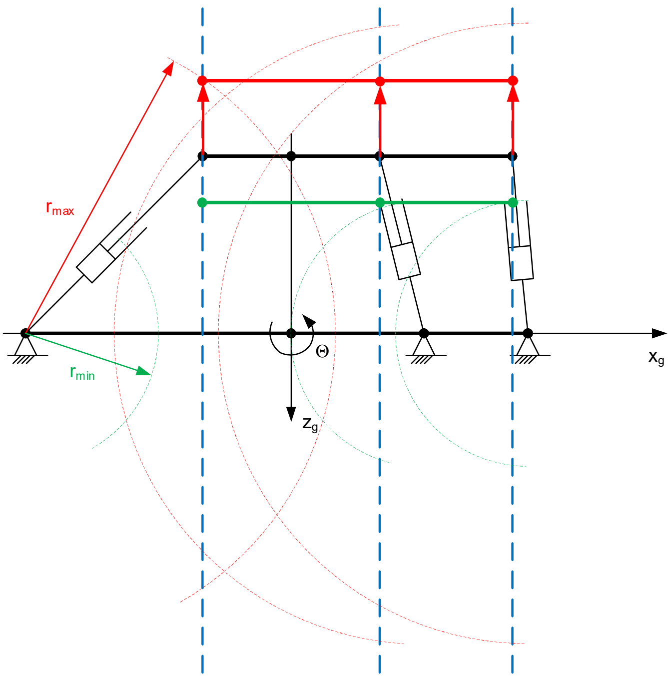

Fig. 1 Principle of the NISER method with the movement (blue), the upper limit (red) and the lower limit (green) in heave direction of the moving platform

The following steps are supposed for a geodetic oriented coordination system. Of course, any other coordination system may be used, too. For the following example (Fig. 2) a movement in heave is assumed. In this case all upper gimbals will move along their z_g-axis (blue dashed line). The maximum and minimum lengths are known for all actuators. This implies that the extreme positions of the joints can be found on a circle with the radius of the maximum (red dotted line) and minimum (green dotted line) length. Therefore, any mathematically possible extreme position is defined to be an intersection point of a radius with a position of a gimbal in heave. This approach leads to a quadric equation with, in theory, real or complex solutions.

In an existing motion system, a complex solution will not occur as long as the structural integrity of the physical system is ensured because a complex solution implies that a pair of a lower and an upper joint has reached a distance which is bigger than the maximum or smaller than the minimum length of the connecting actuator. This is only possible in case the actuator or a gimbal is broken. For this paper it is assumed that such severe mechanical defects are avoided e.g. by a solid mechanical construction and, therefore, does not need to be discussed here. A real solution may have one or two results. Finding only one solution implies that the current actuator has reached an extreme position while two results indicate that looking at the current actuator some movement is still possible.

It is obvious that this approach will work for the rotational degree of freedom, too. Instead of a linear movement one has to use a circle around the rotational reference point, for example the eyepoint of the pilot within the simulator. Looking for the intersections of both circles, again, on will find a quadric equation. Repeating this step for all actuators in all degrees of freedom results in a set of solutions. With respect to the current position of the moving platform the two nearest solutions can be considered as the limit that can be reached for the actual degree of freedom.

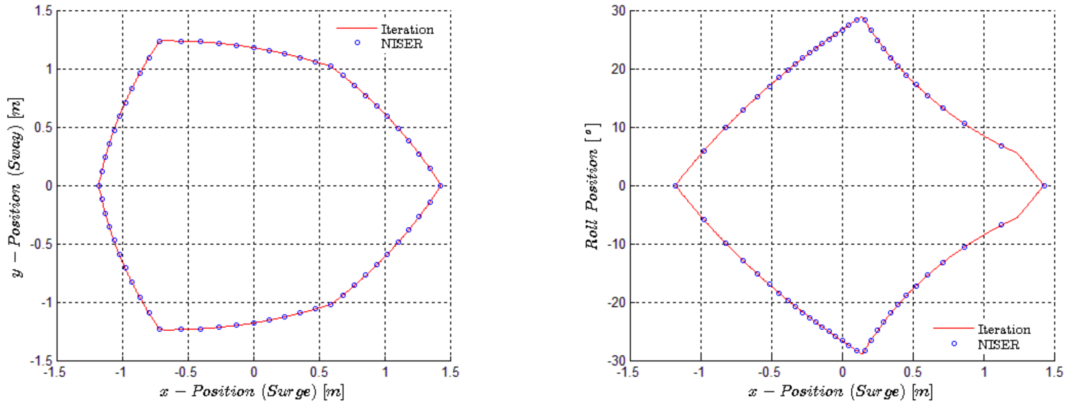

Fig. 2 Space envelope calculation of the AVES motion system in surge/sway (left plot) and surge/roll (right plot) direction each plot compares the results of a current iterative method (solid) with the results of the NISER method (circles)

This approach can be used for a three-dimensional system, too. The movement of the gimbals are, again, defined as a linear or circled line. But the actuator end-joints may reach any extreme position on a spherical surface with a radius of the maximum or minimum length of the actuators. Therefore, the extreme points which can be reached are the intersection points of a sphere and a line. Again, the equation to find one of those intersection points is one of a quadric nature. A mathematical description including an example for a single degree of freedom is given in [22]. Fig. 2 gives an example for the AVES motion, a standard Moog MB-EP-6DOF/60/14000 hexapod system. The NISER method is used to find the space envelope in surge/sway and surge/roll direction. The solid line is the result of the NISER algorithm while the markers along the path represent the results of an iteration method according to [18].

IV. The Limiting Functionality

There are at least two reasons to use limiting functions in addition to a fully parametrized cueing algorithm. First, there is always a chance that for one reason or the other an unforeseen maneuver is made. A second reason may be that the training crew reacts differently to what is expected. Both reasons may lead to a more excessive reaction of the motion system. In order to disturb the training in the least possible way the cueing software should try to avoid any actuator limit, especially a forced stop at the end of the travel range. On the other hand, these situations are not normal during usual training operations. That is why it could be acceptable that the motion system reacts somehow strange but without any sudden or hard stop and the training will not be severely disturbed.

In contrast to other methods, NISER identifies the proximity to a space limit with respect to those dof in which the motion platform is commanded by the control algorithm. Therefore, it is possible to prevent the platform from approaching a limit of any single dof independently. Obviously, the space limit of the current degree of freedom is influenced by the position of the motion platform in all other directions. The easiest way to deal with all these influences is to take this characteristic into account as an independent external constraint. Therefore, for the following section it is assumed that the limits of the current dof will change due to unforeseen and unalterable dependencies. This occurs e. g. due to the movement of the platform in another dof.

A. Translational Degrees of Freedom

For the translational degrees of freedom figure 3 gives an overview of the mechanical substitute model for the solution proposed by this paper. The main idea is that the degree of freedom which the motion platform is moving, can be represented by a motor-driven slider in a fixed tube. The motor is controlled by an algorithm analog to the cueing filter of the motion system. If the slider approaches a limit, a spring-damper-unit ensures that the movement will be decelerated and, if necessary, stopped smoothly. As the space limits are affected by the movements in all other degrees of freedom the absolute limit is varying independently. As a consequence, the space limit left in the given degree of freedom can change even though its position does not change. To address this fact the substitute model includes two independently controlled actuators that drive the limits on both sides.

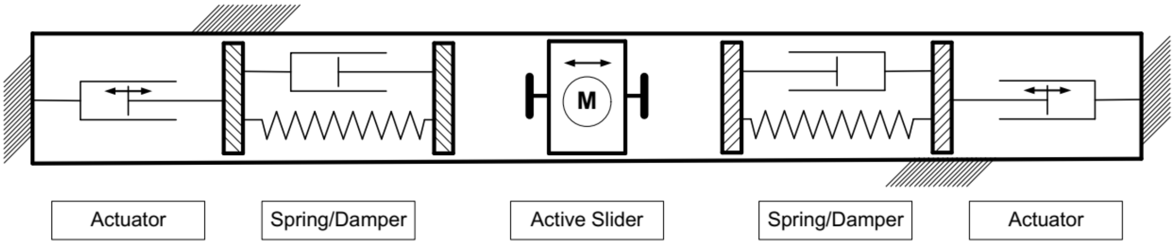

Fig. 3 Mechanical Substitution Model of Limiting Functionality for Translational Degrees of Freedom. A motor drives a slider in a fixed tube between variable limitations and smoothly decelerated by a spring-damper system on both sides.

The presented approach benefits from the fact that the output signal of the washout filter for the translational degrees of freedom is a translational acceleration. For this it is easy to implement a mathematical model according to the method given above without any discontinuous accelerations. Special care needs to be taken when choosing the parameters for the spring load and the damping coefficient. There is a danger to implement an oscillating system which might cause vibrations that will disturb the perception by the pilot much more than necessary.

For this paper it is sufficient to presume that the movement of the independent actuators is unknown. The advantage of this approach is that every dof can be treated independently which makes it easier to fix the parameters. The disadvantage is that, with given parameters, unforeseen inputs may lead to unwanted outputs. For future versions of the limiting function it can be helpful to extrapolate the current platform movement due to the calculated platform positions, again, on a non-iterative basis. By using such a functionality, it is at least possible to predict the tendency of the usable space and to implement e. g. a more flexible adaptive end stop protection.

B. Rotational Degrees of Freedom

For the rotational dof things are a bit more challenging because the washout filter response to both, a low-frequent translational acceleration and a high-frequent rotational input is a rotational attitude. To gain a rotational acceleration signal from an angle by deriving the signal is disadvantageous in a discrete model because one will find discontinuous velocities and accelerations at every single time stamp. This leads to unwanted (artefacts) effects after integrating the signal back to an angle, again. On the other hand, a simple limitation of the angle inevitably results in a noticeably rotational acceleration. Having in mind that the limit itself may change due to movements in other directions, this is even more a problem. Therefore, another approach is chosen to handle with this. Figure 4 shows the basic principle of the function.

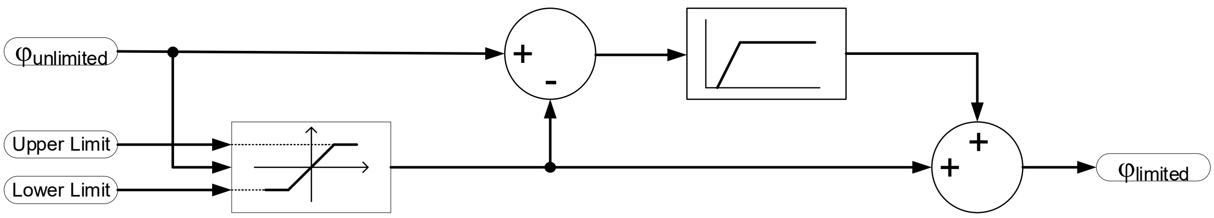

Fig. 4 Mathematical Model for a Basic Limiting Function of Rotational Degrees of Freedom

The basic idea is to limit the input signal and to add a decreasing difference between the limited and the unlimited signal. This is achieved by high pass filters which differ between the limited and the unlimited signal before adding the result to the limited signal. As a consequence, on one hand a smooth reaction is ensured because at the beginning of the limitation the high pass filter shows the pure difference leading to an unchanged limited signal. Later on, the high pass filter will reduce the difference to zero. By adding that high pass filtered difference to the limited signal the output approaches the target value. Because of the integrator within the high pass filter a slow return to an unlimited value is ensured if the input signal reaches a value between the limitations.

Obviously, on the other hand, this means that the limit given by the NISER method will not be met during the whole time, especially at the moment this limit is reached. In AVES this problem is tackled by a safety margin added to the current limits. Unfortunately, this may lead to a situation where the upper limit may fall below the lower limit, e. g. when the upper and the lower limits are very close to each other. Therefore, the given limiting function is replaced by a function that reduces the input signal when it is above the upper limit minus the safety margin and/or above the lower limit plus the safety margin. For this, a factor is calculated which is zero when the input signal is within the limits and one when the space limit is reached. This factor is furthermore weighted by a weighting parameter to be able to adapt the limiting function to the needs of the current scenario. By using the reciprocal of an e-function with this weighted factor as the power the input signal can be reduced sufficiently. The following equations represent the situation for the upper (positive) limit:

$$x_{\text{limited}} = e^{-weightingfactor \cdot (x_{\text{unlimited}} - (limit - safetymargin))} \tag{3}$$

with

$$\left(x_{\text{unlimited}} - (limit - safetymargin)\right) \rightarrow [0 \ldots 1] \tag{4}$$

C. Proof of Concept

In order to demonstrate the effectiveness of the proposed solution a take-off maneuver that has been performed in the simulator is repeated in an off-line emulation of the motion system. The emulation consists of the same software architecture as that of the motion control computer of the AVES motion system. Only those components that directly control hardware or depend on hardware signal input are adapted or bypassed. Therefore, the emulation runs with the same motion control algorithm including those parts done by DLR.

The maneuver chosen for this test is a rejected take-off run. After the acceleration phase where the aircraft increases speed with full thrust set at the start one engine stops just before reaching the decision speed V_1. In order to stop the aircraft, the pilot brakes without using reverse thrust but with the running engine set to idle. Due to the asymmetric thrust after the break-down of the engine the aircraft changes its direction which needs to be compensated by rudder inputs. This maneuver results in a long-lasting longitudinal force due to the braking accompanied by lateral forces due to keeping the aircraft in runway direction. As a result, the simulator cabin pitches down and moves left/right accompanied by some corresponding roll reactions at the same time.

Because this is one of those maneuvers that are part of a common training syllabus, it determines the parameters of the cuing algorithm. In many training simulators the longitudinal forces are represented with a higher gain factor than the lateral ones. For the tests represented in this paper the lateral gain is increased in a way that the motion system is not able to perform the maneuver without touching the space limit. Fig. 5 shows the input signal generated by the aircraft simulation model for the specific forces in surge and sway direction and the response of the motion system. For the following figures, longitudinally related signals are presented in red, laterally related signals are shown in blue.

The graph shows the specific forces $f_{aa,in}$ that are generated by the simulation model of the aircraft and received by the motion system (solid line), the specific force $f_{aa,out}$ derived the cueing filter algorithm (dotted line) and the specific force $f_{aa,out,lim}$ after the limiting function restricted the filter output in order to keep the response of the motion within the space limits (dashed line). The last signal is the force perceived by the simulator crew, provided that the actuators can physically follow the commanded signal.

The maneuver starts with the aircraft standing still aligned with the runway just before the take-off run. At 2 s start thrust is set and the aircraft accelerates in longitudinal direction. The motion system responds with a quick, but short acceleration in surge and a relatively slow pitch rate. This is followed by a slowly decreasing pitch attitude due to the decreasing acceleration. This is a consequence of the decreasing thrust of the simulated engines accompanied by an increasing drag due to an increasing speed. After 43 s the engine failure occurs. Because of the asymmetric thrust lateral forces take place. They are a strong indication of what happens before any signs of failure can be noticed in the cockpit. Therefore, this response of the motion system is important for the training. At the same time the acceleration is reduced due to the failing engine. During this phase the pilot performs lane-keeping activities, sets the thrust of the remaining engine to idle and stops the aircraft before the end of the runway. Within the simulator cockpit this results in a quick negative surge acceleration and a slow pitch-down response accompanied by roll and sway movements. At the moment the aircraft has stopped the motion platform pitches up back to its neutral position.

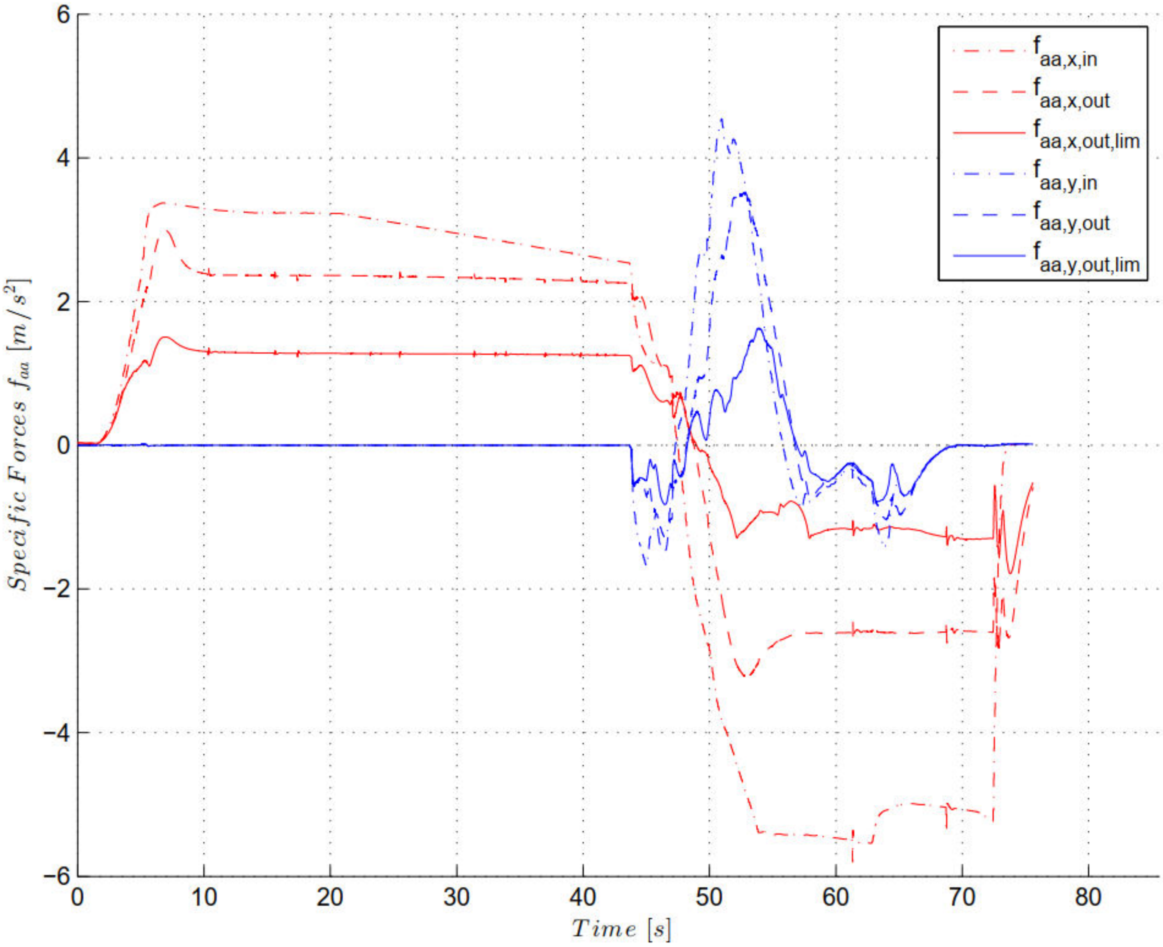

Fig. 5 The specific force input signal for a rejected take-off maneuver due to an engine failure before V_1, input (dash-dotted), the response of the washout filter algorithm (dashed) and the limited simulator response (solid)

Fig. 6 shows the results of the NISER method in consequence of this maneuver and the actuator lengths of the motion system. The upper graph plots the current limits of the four relevant degrees of freedom, the longitudinal (surge) distance, the lateral (sway) distance, the roll angle and the pitch angle until the space limit is reached. The rotational limits are represented by dashed lines, the translational by solid lines. Again, the red graphs represent the degrees of freedom in the longitudinal direction, surge and pitch, while the blue graphs represent the lateral direction, sway and roll. For all degrees of freedom, the two graphs show the usable space up to the limit in the positive and negative direction. For example, while the platform moves forward at the start of the maneuver the value for the longitudinal limit decreases in positive direction while it increases correspondingly in the negative direction too. At the same time and because any movement in surge reduces the space envelope in sway, the positive as well as the negative lateral distance to the limit is reduced.

The following Fig. 7 gives a zoom view to the time period discussed in detail. Between 44 s and 58 s the space which is left for the rotational dof is reduced at least in one direction. The distance between the current position and the space limit for the roll and the pitch angle is less than 0.5 rad or 3 °. In order to understand how small the remaining space is, one has to look at the current actuator lengths in the lower graph. There the values are given for the two most critical actuators of the AVES platform. At the most critical point actuator no. 3 has only about 50 mm room left until it reaches the end stop position. Again, one should note the limited system response in Fig. 5, where both the limited and the unlimited filter algorithm response is given. It should be pointed out, that, in case no limiting functionality is actually given, much more space and therefore actuator travel is needed than really exists. As a result, the motion would run into a forced stop during this maneuver.

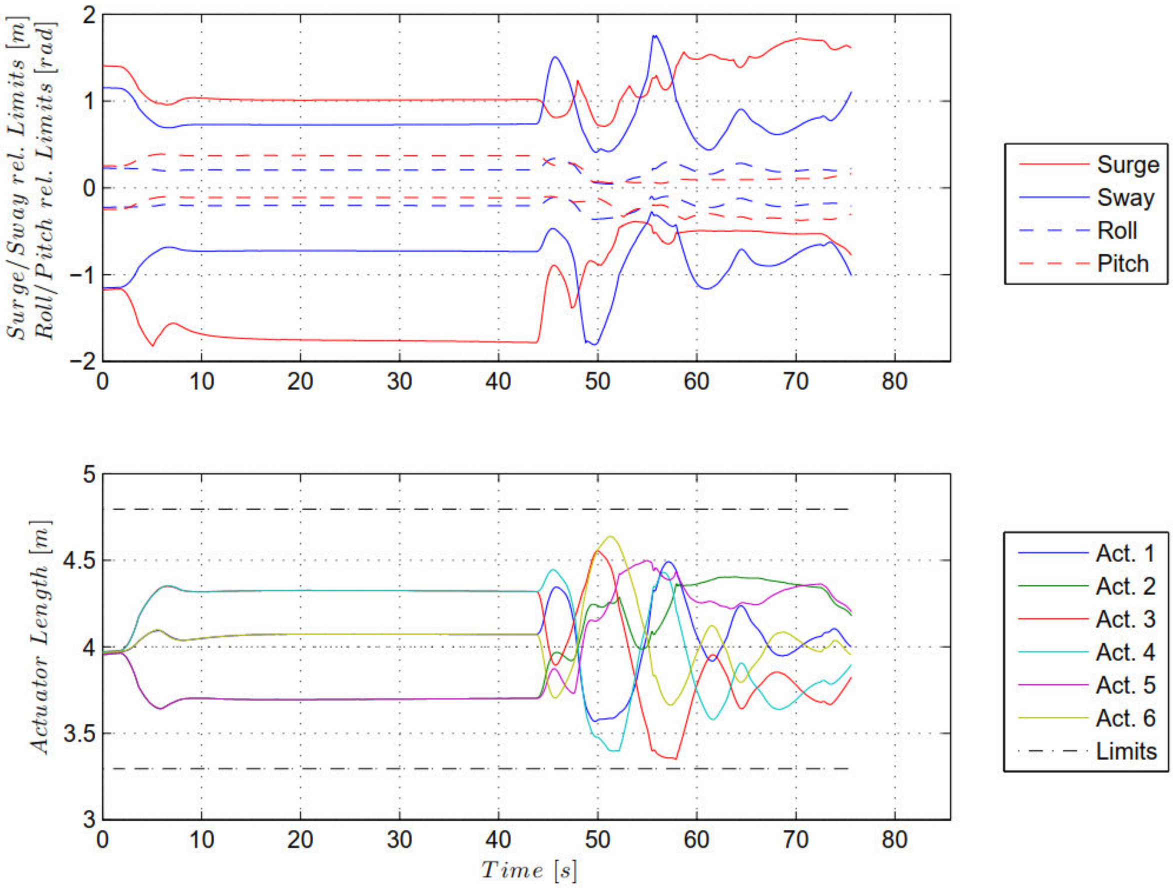

Fig. 6 Relative limits with respect to current position in surge, sway, roll and pitch (upper graph) and current actuator lengths during the simulator maneuver (lower graph)

V. Conclusions

This paper proposes a non-iterative method to calculate the distance between the current motion position and the space limit in any dof. Based on this method it is possible to establish an effective method to keep the moving platform away from the limits in order to avoid sudden and strong accelerations during the simulator flight.

But avoiding the space limits is only one aim. But it is the condition for the second one, to reduce the disturbance of the simulator crew to a minimum in such a situation. For this paper it is accepted that the simulator crew may be exposed to a certain amount of unexpected accelerations. It is furthermore assumed that these unexpected accelerations shall not distract the pilots from the current training task even though this requirement is less than poor defined. Here, this condition is fulfilled if the crew recognizes a somehow queer movement but does not feel any fear or concern with respect to a sudden response of the motion system.

As a result, the pilot's perception may be disturbed even though no rapid acceleration is performed by the motion. Thus, it is better to avoid touching the space limits by a proper parametrization of the score filter results which are of a far better quality than to rely on a limit protection. But if for any reason this is not possible it should be better for the simulator crew to perceive an unexpected acceleration due to a limiting functionality than to observe a forced stop of one or more actuators.

Based on these assumptions two functionalities have been implemented that complement the AVF algorithm of the AVES simulator. For the translational signals a spring-damper system is adapted because these filter output signals are accelerations, too. The main difference is that the mounting point of the spring-damper system vary its position which needs to be addressed in the model of the limit function.

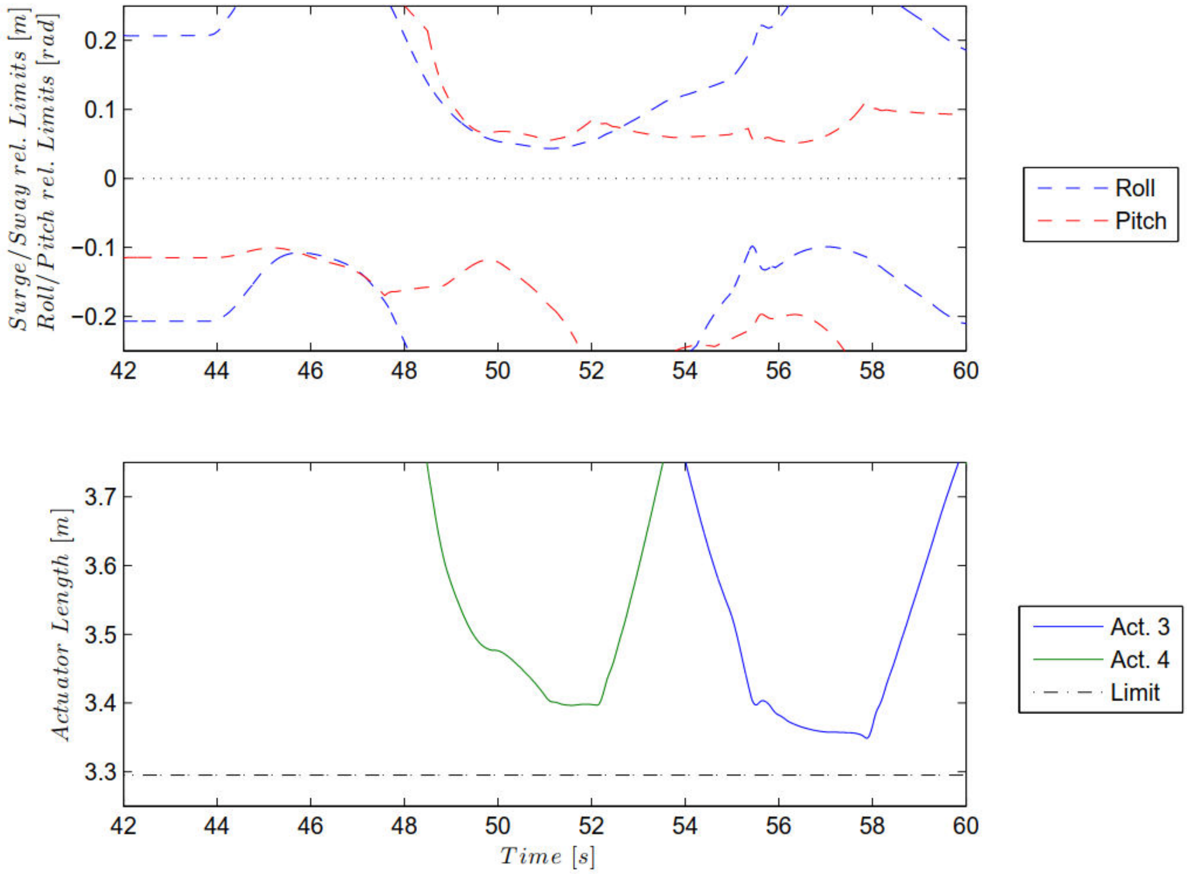

Fig. 7 Relative limits with respect to current position in roll and pitch (upper graph) and length of critical actuators no. 3 and no. 4 during the simulator maneuver (lower graph)

For the rotational filter output signals a more complex approach needs to be used because those signals are angular positions. To avoid sudden accelerations due to the position-limiting a high-pass filter is proposed to reduce those accelerations. This high-pass filter manipulates the difference of the limited and the unlimited signal at the beginning. The result will be added to the limited signal. This results in an unlimited signal at the start of the limiting which will be reduced to the limited signal after a while. Due to this behavior a certain safety margin for the space limit in addition to the calculated remaining space needs to be considered.

Finally, the effectiveness of the proposed methods is demonstrated. For a rejected take-off maneuver with one engine failing just before the decision speed, the parametrization of the motion cueing algorithm is set to improper aggressive values. Without a limiting function, this would force the motion system to move into a position where one or more actuators are reaching their final stop position. The proposed limiting function prevents the motion system from reaching hard limits.

VI. Outlook

With this NISER based limiting functionality, another important module complements the AVF at the AVES simulator. The impact to the Objective Motion Cueing Test should be demonstrated. It is supposed to be zero due to the fact that, by design, no manipulation is expected below the given limits. Further work needs to be carried out to evaluate the influence of the limiting function to the simulator crew's motion perception. Furthermore, this configuration needs to be tested in an approved flight simulator for a representative selection of training maneuvers. By doing so, the evidence of a technique which is at least equivalent to existing motion cueing algorithms shall be demonstrated.

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