INVESTIGATION OF PARALLEL KINEMATIC MECHANISM STRUCTURES FOR HAPTIC DEVICES

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Abstract
Today modeling and simulation tools like FE (Finite Element) and MBS (Multi Body Systems) simulation tools are commonly used within mechanical engineering. These types of tools offer capabilities of Virtual prototyping (VP) with the possibility to investigate and explore a product before a physical prototype is manufactured. This can reduce the number of physical prototypes needed and save both time and money. These tools are also well known to be an effective means to support the process of verification of formulated requirements. They can be used e.g. for evaluation and selection of alternative solutions or as a final check or optimisation of a solution concept. The use of these kinds of tools can be even more effective if an information framework for handling the information created during the verification process can support them.

The outline of such an information framework has been presented by Andersson [1], [2], which support traceability and reuse of partial result created during the verification of a specific requirements attribute as well as a possibility to study the effects that changes in the requirements specification have on product properties. This type of framework need a fine granularity of information, to be able to reuse partial results e.g. component simulation models but also that the models are structured such that we can reuse them in new model configurations.

This paper presents an investigation of 6-dof haptic devices based on parallel structure that can be used in a surgical training simulator for temporal bone milling or as a 6-dof input-output teleoperated haptic master device. This investigation follows the verification process outlined by Andersson [1], [2], where the haptic devices in this case the product concept to be evaluated. The basic idea behind these concepts is to develop a haptic device with a large workspace and high stiffness within this workspace based on modeling and analysis of two different concepts. The study will concentrate to find a way to measure performance parameters to be able to evaluate and compare different structures.

Key words: Haptic devices, parallel kinematic structures, modeling, simulation, MBS

1 Introduction
Haptic devices are robots that can sense and feel what the operator discovers in a virtual world e.g. such being used for medical simulations or in teleoperated input-output master devices where the system can be operated over distance. To use haptic devices as input-output devices for virtual reality games is another growing field of application.
The work described here is related to the use of haptics in applications of medical simulations where manipulation capabilities and force/torque feedback in six degrees of freedom is needed, during surgical procedures of hard tissue. Due to the stiffness of bone, stiff contacts between the objects and probe will be required and so specific attention is given to this issue in the investigation and analysis. The mechanical structures that currently are used for such devices include serial as well as parallel structures. However, parallel kinematic structures have some significant advantages compared to serial ones, e.g. high stiffness, high accuracy, low inertia with the actuators located on the fix base, thus enabling high accelerations.

An initial literature review of haptic input-output devices has been performed to identify candidates for being the best structure [6]. Three different mechanisms were considered for the structural analysis and comparison of performance parameters. Two of these three have so far have been analysed and are treated in this paper. The first one is a variant of the Stewart-Gough mechanism [6], which is a 6 dof kinematic structure with six parallel legs connected to the moveable platform via universal, spherical and translational joints to the base shown in figure 1(left). The linear motions are achieved by linear actuators. The second mechanism is a new family of unsymmetrical parallel kinematic structures called TAU shown in figure 1(right) consisting of three arms connected to a fix base where the device is actuated by rotational motions in this case. This structure is a variant of structures being investigated in research and student projects at KTH, Machine Design [3], [4],[5],[8].

The development of this type of products require computer models for specifying demands as well as models for e.g. definition of product shape, evaluation of product properties, documentation of performed analysis and tests. For development of a high performance haptic device, 3D-CAD models as well as MBS models will be required for simulation and performance prediction, and for control system compensation to obtain advanced performance [9]. This paper will discuss the development of a haptic device, where the approach to general methodology for development of haptic devices, suggested by Khan et al in [7], will be combined with the information framework suggested by Andersson [1]. The main process steps in this methodology are; requirements specification, conceptual design, simulations and device design. The models and analysis discussed in this paper deals with the conceptual design phase, but with the perspective in mind that the same performance parameters are
investigated many times during the development. This reveals the need to make all previous activities possible to retract and if wanted reuse for new investigations.

2 The concept verification process

The series of activities being part of the process of evaluating the selected design concepts will follow the outlined verification process by Andersson [1], [2]. This process aims to enable traceability and reuse of models being used in similar situations or for similar products.

The main idea of this process is to define the activities involved in this process and to describe the results being produced as well as relations between activities and results. It is also related to a description of the design process, in this case a stage-gate model is used, in which the process is divided into a number of, predefined phases with gates between them. The design phases being considered for this application are; requirements specification, conceptual design, simulation and device design. Decisions are taken continuously during the design work, but major decisions are concentrated at the predefined gates between major design activities or phases.

The verification activities occur between the gates and are focused on detailing and resolving uncertainties about the actual concept, that is, on gaining knowledge about the concept. These activities are triggered by the specifications that define the target values for the properties of the proposed product. These activities can all be seen as part of a verification process that iteratively evaluates all critical requirements, either by simulating behavior or by using other sources of information, including colleagues and old designs. Representing these activities and the results of these activities will enable traceability and reuse of simulation models and thus make this evaluation process more efficient.

![Figure 2: The concept verification process for the haptic device, after [1].](image)

In figure 2, we have illustrated the concept verification process, taking place during conceptual design of the haptic device. The main activity in this process is “investigate problem”, where the problem is whatever is unknown about a requirement and needs to be further investigated. In this paper we will focus on two properties to investigate, i.e. device workspace including orientation of the device and Tool Center Point (TCP) force performance. The first investigation deals with the requirement to position and orient the TCP
while the second investigation aim to determine the required performance in terms of needed force/torque from actuators. The database symbols indicate that for each step in this process there are a number of predefined models that may be candidates for use in solving an actual problem. The type of models that are needed to handle and document the data created during the verification process [2] is illustrated in figure 3.

3 Requirements on the device

The specifications given here have been obtained in dialogue with a tentative user, in this case a brain surgeon. It should be noted that it is difficult to obtain specific requirements since the application domain is completely new and unique. The specifications should hence be treated as preliminary and as giving a rough estimate for a first prototypical design. From qualitative perspective the specifications give however a good enough starting point. The initial requirements for the new haptic device (see the requirement specification box in figure 2) are given below

- The device should have 6 actuated degrees of freedom
- The whole device should fit within the space of 250x250x300 [mm]
- The translational workspace should be a minimum of 50x50x50 [mm] with no singularities within that space.
- The rotational workspace should be ±45 degrees in all directions with no singularities within that space
- The stiffness of the device including actuation and control should be a minimum of 50 [N/mm]
- The TCP force performance should be at least 50 [N] in all directions.
- The torque performance around TCP should be at least 1 [Nm] in all directions.
- It should be possible to place it on a table in front of the operator, easy to access for the user.

4 Conceptual design

In haptic devices that currently are available on the market or at a prototype stage, both serial and parallel structures are being used. However, since parallel structures have some significant advantages compared to serial ones, e.g. high stiffness, high accuracy and low inertia, we have chosen two concepts based on parallel kinematic structures. The chosen concepts shown in figure 1 and 4 are based on an initial review of existing structures and
devices [6]. These two concepts are scaled to fit in the same virtual box with the size of 245x245x300 [mm] in the modelled normal position, see figure 4.

Next in turn in this design phase is to investigate that the performance properties of these concepts are sufficient by utilizing the verification process described earlier. In this paper we focus on investigating two main properties which are formulated as two problems to investigate, these are;

1. What is the device workspace?
2. What is the force/torque performance around TCP?

Based on the first problem definition we define two questions that need to be investigated; “What is the maximum workspace?” and “What are the maximum rotation possibilities in all 3 rotation axis within the workspace?” Based on the second problem definition we can define the question “What is the required force/torque performance of the actuators to achieve the wanted force/torque performance around TCP?”, see figure 5.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Question</th>
<th>Model specification</th>
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<tbody>
<tr>
<td>Workspace</td>
<td>Maximum workspace</td>
<td>Model Spec 1</td>
</tr>
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<td></td>
<td>Rotations within selected workspace</td>
<td>Model Spec 2</td>
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<tr>
<td>Torque/Force performance</td>
<td>Performance on actuators</td>
<td>Model Spec 3</td>
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Figure 5. Models needed for the verification process, one set for each concept to evaluate.
Once when we have formulated the problems to be investigated, questions to these problems and defined what kind of models and modelling tools that we want to use, we can start the modelling work. As a means for solving the problems in figure 5 we have chosen to specify that we should use ADAMS MBS software to be the main modelling tool. Modelling of the two devices follows the same principle steps. For the workspace problem we do the following:

- Create a parameterized ADAMS model of the concept structure
- Analysis of the outer boundary of the workspace
- Selecting a suitable position for an assumed wanted workspace of 50x50x50 [mm].
- Analysis of how much the TCP can rotate in all eight corners (applying a torque or rotation at TCP).

For the torque/force performance problem we do the following:

- Create a parameterized ADAMS model of the concept structure
- Use the same workspace cube as above and position TCP in the corners for a series of analysis.
- Analysis of what force or torque is required by the actuators for a wanted force or torque performance at TCP in all six degrees of freedom (by applying a force or a torque at TCP).

4.1 Workspace analysis

This task starts with modelling the structure for each concept in ADAMS. Once we have this model we have used the following approach to analyse the workspace:

- A vector force assigned to TCP that is forcing it to sweeping the outer workspace boundary by using an expression with $\sin(\omega \times \text{time})$ and $\cos(\omega \times \text{time})$ for X resp. Y force component. The Z component is increased stepwise for every full turn of the force.

- Defining restrictions on allowed translations (Stewart-Gough) and on allowed rotations (TAU) to obtain realistic movements of the arms in the mechanisms.

Based on the obtained workspace a location of a wanted workspace of 50x50x50 [mm] is identified and the following approach is used to analyse rotational properties of TCP:

- For each corner of this workspace cub, the actuators are deactivated and a rotational motion is applied in all 3 axis directions and the maximum rotations are measured.

**Concept 1: Stewart-Gough platform**

This concept was modelled in ADAMS as shown in figure 6 (left). The platform is connected by universal joints with upper links and the upper links are connected to the lower links by spherical joints. The lower links are connected to the base by liner active joints. The model provides six actuated degrees of freedom. The translation workspace provided by the model in X and Z direction is $\pm 55$[mm] and along Y-direction from 260 [mm] to 350 (90 [mm]) shown in figure 7.
Figure 6. ADAMS model of Stewart-Gough platform for workspace analysis (left) and selected workspace (right).

Figure 7: Workspace for concept 1 in XZ-plane and in 3D space at constant orientation.

The maximum rotational workspace of concept 1 was determined by selecting a cube of 50[mm] within translational workspace figure 6 (right). Analyses were performed at each corner to determine the maximum possible rotation without violating the restrictions.

The results show that the TCP provides maximum rotation when it is rotated along one axis’s. In case of applying rotation around multiple axis at the same time then the range of rotation is decreased. Also it is noted that the range of rotation is similar at corner 1, 2, 3, 4 and it ranges from ±50 degree in x,y,z direction while in combination it ranges from ±35 degree. The ranges of rotation at corner 5,6,7,8 are smaller than the corner 1,2,3,4. This is due to upper stroke limit of actuators, and it ranges ±25 degree in all 3 axis. But at each upper corner along one axis at can provide rotation up to 55 degree.

**Concept 2: TAU**

The TAU concept was modelled in ADAMS using a combination of revolute, universal and spherical joints as shown if figure 8 (left). The joints whose rotation have been limited in this analysis is shown in figure 8 (right).

The workspace in figure 9 is shown for the identified most favourable position of arm3, which is when it is oriented -40 degrees compared to arm2.
The maximum rotational workspace of concept 2 was investigated in a similar way as for concept 1. A cube (50x50x50 [mm]) was selected within translational workspace, see figure 10 (right). However it turned out that the initial TAU concept was difficult to position within the workspace which indicates that there exist singularities. The approach taken was to modify the upper arm (arm3) and allow it to rotate only around the z axis, see figure 10 (left). However this modification also resulted in reduced degrees of freedom to five instead of six. The idea here is to add an extra actuator at TCP taking care of the rotation around Y axis. Thereafter analyses were performed at each corner to determine maximum rotation without violating joint restrictions.
The results from the rotation analysis showed that the rotation angles for X and Z directions are good, at least $\pm 50$ degrees in all eight corners, when rotating one axis at a time. The Y axis is not possible to control with this structure as earlier mentioned. This makes the combined rotation analysis hard to evaluate and needs to be further investigated and will not be discussed here any further.

4.2 Force/Torque performance analysis

To achieve a wanted force performance around TCP we need to analyse what force or torque is required by the actuators. To estimate the force or torque that is required by the actuators we have used the following approach:

- Locate a workspace in the form of a cube within the total workspace and position TCP in all eight corners.
- For each corner all actuators are being held fixed during the stiffness analysis and a linear increasing force (0 – 50 [N]) and torque (0-50 [Nmm]) is applied at TCP and resulting torques/forces at the actuators are being measured.

**Concept 1: Stewart-Gough platform**

To analyze the force and torque that is required on actuators (link), the same cube was selected as for rotation analysis and a combination of forces (X,Y,Z) and torques was applied to the TCP of the platform. The forces that are required to keep the platform at that specified location were measured, provided by linear actuators. The result shows that at corner 1, 2, 5 and 6 low forces are required while for corner 3, 4, 7, and 8 maximum forces are required as shown in table 1.
### Table 1

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#### Concept 2: Modified TAU

To analyze the torque that is required on actuators (link), the same cube was selected as for rotation analysis and a combination of forces (X,Y,Z) was applied to the TCP of the platform. The torques, provided by rotational actuators, that is required to keep the TCP that specified location was measured. The result shows that ring1 requires the motor with highest torque capacity while for arm1 and arm2 we can use smaller motors. This is also good because the motor at ring1 is placed in the fix part of the structure while the smallest motors (arm1, arm2) are placed on the moving part of the system. It should however be noted that Corner 1 require a quite high torque for arm2, indicating that this is weak spot in current workspace.

### Table 2

<table>
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<tr>
<th>Corner</th>
<th>Max.Torques arm1(Nmm)</th>
<th>Max.Torques arm2(Nmm)</th>
<th>Max.Torques arm3(Nmm)</th>
<th>Max.Torques ring1(Nmm)</th>
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### 5 Discussion

The activities that been discussed on the evaluation of concepts to a new 6 dof haptic device that follows that path described in Andersson [1], [2] and in section 2. A principle view of this process for these two concepts, with its related models during this evaluation is shown in figure 10. It starts with the requirement specification and the two concepts and ends with compiling answers to be part of a decision basis.
This investigation aimed to find measures that can be used for comparing different 6-dof structures of haptic devices as a first step and later also to define an approach for optimizing selected mechanisms for maximum workspace. The parameters that we have so far are volume of the device (max size) operational workspace and the performance parameters in terms of maximum rotations and required actuator torques or forces. It is hard to define a measure that compares the actuator performance with respect to device volume or operational workspace since one concept requires torques and the other forces from the actuators. What can be a possible measure is the ratio between operational workspace and device volume, here named as effective volume:

\[ V_{\text{eff}} = \frac{W_{\text{op}}}{V_{\text{dev}}} \]

If we want to compare concepts based on solely rotational actuators we can define a measure for torque efficiency, \( T_{\text{eff}} \) and for those based on linear actuators only force efficiency, \( F_{\text{eff}} \), where:

\[ T_{\text{eff}} = \frac{T_{\text{max}}}{V_{\text{eff}}} \], and

\[ F_{\text{eff}} = \frac{F_{\text{max}}}{V_{\text{eff}}} \]
It should however be noticed that in our case when comparing the Stewart platform and the TAU concept we can only use $V_{\text{eff}}$ measure and that it is not possible to make any choice based solely on this measure.

6 Summary and conclusions

In this paper we have presented an investigation the properties of two concepts of 6-dof haptic devices based on parallel structures that can be used in a surgical training simulator for temporal bone milling or as a 6-dof input-output teleoperated haptic master device. The basic idea is to develop a haptic device with a large workspace and high stiffness within this workspace based on modelling and analysis of two different concept mechanisms. The study has followed the outlined verification process as outlined by Andersson [1], [2] to test that process model at the same time as these concepts are analysed and also use it to structure the documentation of this verification.

The analysis of these two concepts has so far revealed some weak spots of the TAU concept, causing a modification to be performed but after that modification both concepts seems to satisfy the initially stated requirements. We have analysed the concepts regarding workspace, stiffness and rotations and as a result of these first analysis we so far consider both concepts suitable to use.

We have also strived to define measure to be able to evaluate and compare different structures. We have so far defined three measures that can be a starting point but more research is needed to define a set of measures that is needed to do such comparisons. Although we find the required stiffness to be fulfilled in all corners of the work volume being analysed, a continuation of this will be to assure that it can be obtained in all positions in the selected work volume and to minimise the variation within that space.

References


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