COMPARATIVE STUDY OF ROBOT-DESIGNS FOR A HANDHELD MEDICAL ROBOT

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Abstract: Robotic systems are used within a great variety of medical disciplines. A handheld robot promises a number of advantages compared to conventional (medical) robots but this approach leads to strict specifications regarding size, weight and dynamic properties. A new hybrid kinematics – the Epizactor – seems to be advantageous and is compared to two well-known parallel kinematics regarding the ratio of workspace and volume the number of kinematic elements, the cost of computation, the stiffness the effects of clearance, actuation (weight), and accuracy using a well-described industrial method for comparison. It becomes clear that the Epizactor has advantages concerning the ratio of workspace and volume, needs a smaller number of kinematic elements and fewer computations, and has less than half the mass than the parallel kinematics. Its accuracy, stiffness and the effects of clearance are comparable. The advantages of this new kinematic set-up lead to a first deployment within the field of medical robotics.

1 INTRODUCTION

Design and evaluation of robotic set-ups for medical and especially surgical applications has been ongoing for the last 20 years. Systems for a vast variety of medical disciplines and deployments have been investigated (Pott PP et al., 2005). One possible solution to provide a useful tool for numerous medical tasks is to use a handheld robot that combines the process control of the surgical task by the surgeon and the accuracy and repeatability of a robot. Within the project "Intelligent Tool Drive" ITD, a handheld robot for orthopaedic surgery is being developed. The intention is to align a milling tool relatively to a patient and to decouple the tool from unintentional hand movements at the handle (Pott PP et al., 2003; Wagner A et al., 2004). A handheld robot has to be as small and lightweight as possible while providing high dynamics for accurate stabilisation of a surgical tool (Wagner A et al., 2004). This most important criterion is mainly determined by the kinematic set-up.

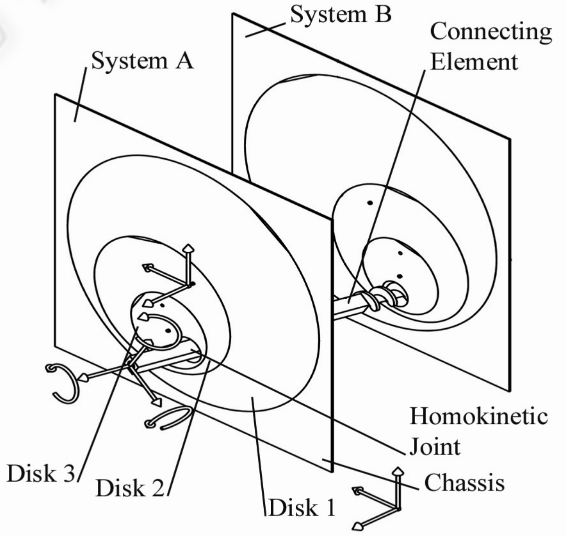

Figure 1: The EPIZACTOR, 6-DOF hybrid kinematics with rotating elements.

Parallel robots are widely used, where high stiffness, high dynamics, or low error propagation

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over the kinematic chains is required, e.g. positioning and stabilization platforms (Huynh P, 2001) and vibration isolation (Chen Y et al., 2004). An obvious advantage is that a parallel robot provides high potential for a lightweight construction. The moving masses of parallel kinematics are low and this leads to low static and dynamic forces (Honegger M, 1999; Huynh P, 2001).

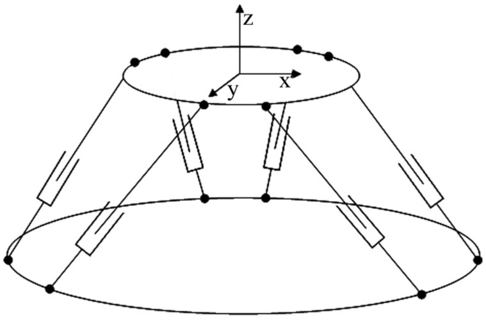

Figure 2: The HEXAPOD, 6-DOF parallel kinematics with actuated prismatic joints in the struts.

Alternatively a new kinematic set-up can be used (). This concept –called "Epizactor"– involves two disk-systems (systems A&B) each described by a planar 3-DOF 4-link manipulator. These two serial kinematic chains act on a connecting element that moves the surgical tool by homokinetic joints with a lead-screw and a prismatic section respectively. Each disk-system uses four links to overcome singularities by redundancy. So this hybrid kinematics uses only rotating elements to provide 6-DOF manoeuvrability (Pott PP et al., 2007; Pott PP, Weiser HP et al., 2004).

The aim of this work is the comparison of a new kinematic set-up with two well-known alternatives for a handheld medical robot.

2 MATERIAL & METHODS

Three different kinematic set-ups were assessed. The well-known Stewart-Gough-platform or Hexapod (Figure 2) with active struts (Gough V et al., 1962; Stewart D, 1965), the Merlet-platform or Hexaglide (Merlet JP, 1988) with base-fixed actuators and passive struts (Figure 3) and the Epizactor (Pott PP et al., 2007; Pott PP, Weiser HP et al., 2004) (). The first two set-ups are based on parallel kinematics while the Epizactor is based on a hybrid kinematics set-up. To describe the set-ups' forward and inverse kinematics as well as the inverse dynamic models a literature research and own considerations were conducted. For the assessment of the actual mechanical design three robots were available. Each is based on one of the kinematic set-ups described and shows a certain state of project ITD.

2.1 Comparison

To compare the kinematic set-ups the method by Kesselring (Kesselring F, 1951) is used. Here a set of criteria is defined and evaluated by one or more experts using a score reaching from 4 (very good) to 1 (poor). To further refine the comparison, each criterion is weighted. Finally for each kinematic set-up the sum of all products of score and weight are added up and lead to a total benchmark for each kinematic set-up. To define the weighting factors the method described by Wenzel (Wenzel R et al., 1971) is used. Here all criteria are listed and each criterion is compared to the remaining leading to a graduation in importance of the different criteria.

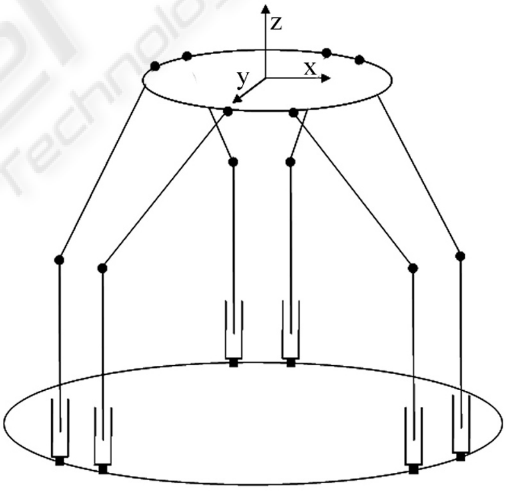

Figure 3: The HEXAGLIDE, 6-DOF parallel kinematics with base-fixed actuates prismatic joints.

To assess the three kinematic set-ups the following criteria were used.

2.2 Ratio of Workspace and Installation Space

Given a certain workspace needed for a specific task, this ratio describes how large a machine will become at least. Especially in a surgical environment the installation space should be as small as possible while the workspace is determined by the surgical task.

To assess this ratio each kinematic set-up was simulated using *Matlab* (The Mathworks Inc, Natick, MA, USA) and a given workspace definition of 40mm translation of the tool in each axis and ±20° rotation in each axis at all times. Using this simulation procedure the three kinematic set-ups were scaled until predefined kinematic restrictions were just not violated but the desired workspace could still be produced. Each kinematic set-up is circumscribed by a cylinder that defines the minimal installation space of an imaginary machine based on the corresponding kinematics. The length of the cylinder is aligned with the tool nearest to the base-platform.

2.3 Number of Kinematic Elements

Kinematic elements are defined as "joints", "struts" or "links", "base", and "tool". The number of kinematic elements can be used as a measure of complexity of a kinematic set-up (El-Shenawy A et al., 2007).

To assess the number of kinematic elements each kinematic set-up was analysed and the elements were counted.

2.4 Cost of Computation

The cost of computation can be a measure for the hardware-effort that has to be made by the control system to compute the forward and inverse kinematic problems in real-time.

To assess the cost of computation for each kinematic set-up the *Matlab*-code was analysed regarding the number of additions, multiplications/powers and trigonometric functions. To compare the three set-ups a computation of both kinematic problems was concerned and all computation steps were summed up. The set-up with greatest number was rated "1" the one with the smallest number was rated "4". In between a linear interpolation was performed.

2.5 Stiffness

Although stiffness is not a kinematic property and system stiffness is mainly affected by the actual design of a machine the three set-ups can be analysed qualitatively regarding the distribution of forces within the kinematic elements. It can be stated that short and compact elements under uniaxial load will be stiffer than flat elements under bending strain.

To analyse the three set-ups the kinematic elements were examined regarding the distribution of force and shape.

2.6 Effects of Clearance

As it can be regarded as one of the major impediments for accurate machine performance clearance becomes one of the most important criteria. Again this is not a purely kinematic feature but the kinematic set-up has an influence on error propagation.

To assess the effects of clearance a score especially for the assessment of parallel and hybrid kinematics was introduced (Pott PP, unpublished). It was assumed that the clearance k_i of i joints of a serial kinematic chain in the most unfavourable case is summed up to

$$k_{tot,ser} = \sum_i k_i \tag{1}$$

For the parallel arrangement of j serial chains it is assumed that the clearance can be treated as

$$k_{tot,par} = \sqrt{\sum_j \left(k_{j,ser}\right)^2} \tag{2}$$

For simplification the clearance in any joint is standardised to "1".

2.7 Actuation / Weight

The actuation of a robot is not a kinematic property but becomes important when size and weight of the actual machine is evaluated. Electromagnetic linear actuators provide high acceleration but a poor force-to-weight ratio. Correspondingly conventional rotating motors deliver high power at high speeds but poor torque when used without gearing (Pott PP, unpublished). So the actuation has an immanent influence on the weight of a machine based on a certain kinematic set-up.

To assess the three kinematic set-ups they were analysed regarding performance needed and theoretical weight. To determine the strut forces of the Hexapod and the Hexaglide corresponding dynamic models were used (Dasgupta B et al., 1998; Khalil W et al., 2004; Wagner A et al., 2006)., dynamic models (Dasgupta B et al., 1998) were used. The Epizactor was assessed using a model based on the iterative Newton-Euler-Method and own considerations regarding the forward- and inverse kinematic problems (Pott PP et al., 2007). As input for the simulation a vibration trajectory with 12Hz and 1mm amplitude was used. This trajectory was applied to each of a set of 680 pre-defined grid-points throughout the whole desired workspace. Additionally the direction of the trajectory and the static forces $F = \begin{bmatrix}20 & 20 & 20\end{bmatrix}^T N$ and moments $M = \begin{bmatrix}1 & 1 & 0.8\end{bmatrix}^T Nm$ were permutated in the main coordinate system directions. Forces, moments, frequency (velocity, acceleration) were taken from the specifications of the handheld robot (Pott PP et al., 2003; Pott PP, Wagner A et al., 2004). Masses and mass-related values of the kinematic elements were taken from the CAD-models of the three available robots. The maximum forces and torques in each actuator were computed. For the parallel kinematics this force was multiplied by six, as the symmetry of the set-up leads to the conclusion that any actuator will have to be able to produce this force. Regarding the Epizactor the torques of all actuators were summed up. To achieve the theoretical weight of the actuators of each set-up the over-all force was multiplied with the specific force-to-weight-ratio of the linear actuators and the rotating actuators respectively. It could be shown from manufacturer's data that an average electric linear motor with a maximum force of about 50N (30s) has a force-to-weight ratio of about 47.2N/kg. The torque-to-weight ratio of an average motor with a gear that allows a torque of 1Nm is about 3.4Nm/kg (Pott PP, unpublished).

2.8 Accuracy

The accuracy of a robot is determined by the accuracy and resolution of sensors and actuators, the adjustment of control parameters, the elastic properties of the mechanics, and the transformation of workspace coordinates into actuator axis positions. As the first three parameters are affected by the actual mechanical design, the latter is dependent on the kinematics-type and actual configuration only.

To assess the theoretical accuracy the tolerable position error of the robot of 0.1mm (Pott PP et al., 2003) was applied to the set of grid-points described above. Doing so, the displacement of the actuators was computed and compared to a realistic accuracy of 0.005mm and 0.0005rad respectively, which can be reached by real encoders used in a mechanical design. A score was introduced that describes the number of points where the accuracy specification is reached.

3 RESULTS

3.1 Comparison

Table 1 shows a summary of the results for each kinematic set-up. The comparison criteria are aligned in rows. The columns show results, ratings and weighted scores for each of the three kinematic set-ups. The results of the comparison and a ranking are summed up in the bottom line. It becomes clear that the Epizactor has advantages regarding the ratio of workspace and installation-space and theoretical weight of its actuators. Additionally it needs less kinematic elements, uses rotating actuators that provide a better performance-to-weight ratio than linear motors, and needs fewer computations for the inverse and direct kinematic problem. Main disadvantage of this new kinematic set-up is the limited stiffness.

3.2 Ratio of Workspace and Installation Space

The Hexapod can be enclosed by a cylinder with a minimal volume of 3941cm³. This leads to a ratio of workspace and installation space of 1:62.

The cylinder around the Hexaglide has a minimal volume of 4247cm³ so the ratio of workspace and installation space can be computed to 1:66.

A cylinder circumscribing the Epizactor has a volume of 1445cm³. Compared with the required workspace this leads to a ratio of workspace and installation space of 1:23.

3.3 Number of Kinematic Elements

The Hexapod and the Hexaglide each consist of a base-platform, a tool-platform, and six legs. Each leg uses two rotating and one prismatic (actuated) joint and a strut. Overall 26 kinematic elements can be counted.

The Epizactor consists of a base, a connecting element (tool) and two identical disk-systems. Each disk-system has 3 disks and a homokinetic joint. The first disk is actuated directly. To drive the 2nd disk a single toothed ring is necessary, to drive the 3rd disk two toothed rings are used and the joint is driven by three rings. Overall 22 kinematic elements can be counted.

3.4 Cost of Computation

To calculate the Hexapod's inverse kinematic problem 60 additions, 132 multiplications and powers, and 174 trigonometric functions have to be computed. The forward kinematic problem can only be solved by an iterative procedure. Within the simulations carried out around 40 iteration steps were necessary for each computation. To compute the kinematics once in both directions 15086 computations have to be carried out.

For the Hexaglide the inverse kinematic problem is solved in the same way and also the forward kinematics needs to be computed by iterations. Here around 10 iteration steps were necessary. To compute the kinematics once in both directions 4046 computation steps have to be done.

The inverse kinematic problem of the Epizactor needs 106 additions, 171 multiplications and powers, and 132 trigonometric functions. The forward kinematics are computed by 31 additions, 115 multiplications and 177 trigonometric functions (Pott PP, unpublished). To compute the kinematics once in both directions 732 computations have to be carried out. One has to consider that the inverse kinematic problem finally is solved by a singularity-robust control algorithm (Chung YG et al., 2000; Pott PP et al., submitted) and does not need to be computed.

3.5 Stiffness

The struts of the Hexapod kinematics can be regarded as pendulum links. Each of the struts is loaded by pressure and tension which must be fully

Table 1: Summary of the results and comparion of the three kinematic set-ups assessed. The comparion criteria are aligned in rows, the results of the comparison, the rating, and weighted results are listed in columns. The bottom lines show the result and the ranking of the three kinematic set-ups. The higher the result the better the set-up is suited for the assessed deployment.

criteria	unit	weight	Hexapod			Hexaglide			Epizactor		
			results	rating	result rating	results	rating	result rating	results	rating	result rating
Ratio of Workspace and Installation Space	1	0.28	1:62	2	0.56	1:66	2	0.56	1:23	4	1.12
Number of Kinematic Elements	1	0.09	26	3	0.27	26	3	0.27	22	4	0.36
Cost of Computation	score	0.02	15086	1	0.02	4046	3.36	0.07	732	4	0.08
Stiffness	rating	0.14	high and constant stiffness	4	0.56	high but variable stiffness	3	0.42	medium stiffness	2	0.28
Effects of Clearance	score	0.19	7.3	2	0.38	7.3	2	0.38	7.1	2	0.38
Actuation / Weight	kg	0.19	7.1	1	0.19	5.6	2	0.38	2.2	4	0.76
Accuracy	score	0.09	300	1	0.09	440	2	0.18	420	2	0.18
Results of the comparison					2.07			2.26			3.16
Ranking					3			2			1

absorbed by the actuated prismatic joint in each strut. As the passive parts in each strut can be designed as stiff as necessary the stiffness of the prismatic joint depends on its design, the construction of the actuator, and the quality of the control loop. The stiffness of the struts is almost constant over the length so it can be stated that the over-all stiffness of the Hexapod in its workspace is constant.

To consider the stiffness of the Hexaglide a similar approach can be used. Differences exist as the struts of the Hexaglide usually tend to be as light as possible as they do not need to be actuated. Also two variations of parallel kinematics with base-fixed actuation exist. One that uses sliders (Hebsacker M et al., 1998), here the over-all stiffness within the workspace can be seen as constant. The version that uses piston-like actuators (Merlet JP, 1988) provides lower stiffness for extended actuators and changing over-all stiffness within the workspace.

Forces applied to the connecting element of the Epizactor are propagated to the disk-systems and absorbed within the planes of the disk systems. The stiffness of the disk-systems in this direction is rather good. Only the force-component within the axis of the connecting element acts perpendicular to disk-system B so that here the stiffness is less good. The stiffness is constant within the workspace as the connecting element can be designed as stiff as necessary.

3.6 Effects of Clearance

The Hexapod is based on six identical kinematic chains between base-platform and tool. Each chain consists of three joints. The clearance $k_{tot,ser}$ of each chain is computed to

$$k_{tot,ser} = \sum_i k_i = 1 + 1 + 1 = 3 \cdot \tag{3}$$

For the whole set-up the score can be computed to

$$k_{tot,par} = \sqrt{\sum_j \left(k_{j,ser}\right)^2} = \sqrt{6 \cdot 3^2} = 7.3 \tag{4}$$

The same assumptions can be made for the Hexaglide and lead to a similar result.

The Epizactor uses two serial chains with 5 elements acting in parallel on the connecting element. The clearance $k_{tot,ser}$ of each chain is computed to

$$k_{tot,ser} = \sum_i k_i = 1 + 1 + 1 + 1 + 1 = 5 \cdot \tag{5}$$

For the parallel arrangement of the two chains, the overall score can be computed to

$$k_{tot,par} = \sqrt{\sum_j \left(k_{j,ser}\right)^2} = \sqrt{5^2 + 5^2} = 7.1 \cdot \tag{6}$$

3.7 Actuation / Weight

The simulations for the Hexapod lead to maximum forces of 55.7N in each strut. Thus the six actuators needed to drive the Hexapod weighs at least 7.1kg.

For the Hexaglide the maximum force needed to drive the set-up is 44.4N. With the same considerations regarding the force-to weight-ratio the actuators theoretically weigh about 5.6kg.

The Epizactor has a maximum torque requirement in the specific actuators of 1.33Nm, 1.53Nm, 0.94Nm, 0.8Nm, 0.95Nm, 1.52Nm, 0.26Nm, and 0.02Nm. So the theoretical weight of all actuators of the Epizactor sums up to 2.2kg.

3.8 Accuracy

The Hexapod can provide the desired kinematic accuracy in 300 of the tested 680 grid-points. These points are located near the main *xz*- and *yz*-plane of the base-platform.

The Hexaglide reaches the desired accuracy in 440 of the tested grid-points. These are distributed symmetrically to the main *xz*-plane of the base. Within a small strip just next to this plane the accuracy is not reached.

The Epizactor reaches the accuracy specification on 420 grid-points. These are symmetrically distributed within the workspace. The desired accuracy is not reached at points were a certain configuration of the disks leads to a very sensitive behaviour of the kinematics.

4 DISCUSSION

Three different kinematic set-ups have been evaluated. The method to compare the three kinematic set-ups refers to the German norm VDI 2222. This method leads to a reproducible result when it is done out by a group of experts. Here a single expert carried out the comparison so a certain bias can be assumed. However as primarily measurable criteria were evaluated, the bias is believed to be small. The graduation of the ratings is rather raw but this simplifies the rating itself. It becomes obvious that the Epizactor provides a number of advantages when compared to two well-known parallel kinematic set-ups. This lead to the decision to design such a set-up within the medical robotics project ITD and for future projects.

It could be shown, that the ratio of desired workspace and theoretical installation space of the Epizactor is about three times better when compared to the well-known parallel kinematics. The desired workspace is derived from the specifications of the ITD project and is described by a cube. If another workspace-specification is taken into account, the comparison will produce different results. The method to simulate the desired workspace and to scale down the kinematic set-up does not lead to an optimization but seems to approximate the actual set-up to this point. This criterion is the most important within the comparison.

The Epizactor needs a smaller number of kinematic elements than the Hexapod or the Hexaglide. However the larger number of common parts within the parallel kinematics simplifies the actual manufacturing of those kinematic set-ups.

The fact that there seems to be no closed-form solution for the inverse kinematics of the Hexapod and the Hexaglide leads to a large number of computations for the forward kinematic problem. In contrast the mathematically well-defined kinematics of the Epizactor leads to only a small number of computations. It has to be considered that the code analysed for comparison is not optimised. Although the cost of computation is unequally distributed between the three kinematic set-ups this criterion has the least importance, as today's computer performance allows even large computations in real-time.

Stiffness is depending on the actual design of a machine and is not an original kinematic property. It is affected by the force distribution in the kinematic set-up and therefore can be regarded quite important as it applies to the robot's accuracy. Here stiffness is analysed qualitatively and leads to the conclusion that the Epizactor appears to be less stiff as forces are distributed through flat rotating elements rather than by robust pendulum supports utilised by the parallel kinematics.

Although the effect of clearance is the second most important due to accuracy reasons the differences between the three set-ups are marginal as it could be shown by the score that was introduced. This can be explained by the fact that the length of the kinematic chains and their quantity compensate for each other. One has to remark that this score can only be applied to parallel kinematics and that experimental results have not yet been made to substantiate this comparison.

While actuation is not a kinematic property this criterion is used to evaluate a theoretical weight of the actuators and hence for the weight of a hypothetically realised machine. During the work on the ITD-project it became obvious that linear actuators seem to provide an unfavourable ratio of force and weight, so that a machine driven by such actuators becomes heavier than a machine driven by rotating actuators considering comparable performance. This also applies when rotating spindles are used because of their additional weight. The parallel kinematics are 3.2 times (Hexapod) and 2.5 times (Hexaglide) heavier than the Epizactor due to the use of rotating actuators in this set-up and its more favourable dynamic properties.

The resolution and accuracy of sensors for linear displacement and rotating angles are limited. So the accuracy of a machine based on a certain kinematic set-up is not only limited by mechanical precision, elasticity and the quality of the control loop but also by the kinematic transformation of tool and axis coordinates. The Epizactor's coordinate transformation seems to be advantageous here.

The discrimination between purely kinematic properties and features of the technical realisation is not easy. This seems not to be a disadvantage as the idea of the Epizactor aims to a practical use of the kinematics in a handheld medical robot.

5 CONCLUSIONS

The Epizactor is a new kinematic concept for a small 6-DOF robot. A first deployment of this approach will be a handheld robot for medical applications. Here sharp restrictions regarding size, weight and workspace exist and it could be shown, that the Epizactor meets the main specifications in a most favourable way.

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