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Automatic Detection of Assembly Mode for a Triglide-Robot

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Abstract— **Robots based on parallel kinematic structures are known to have a small workspace compared to their installation space. To tackle this drawback a workspace enlargement approach using several workspaces going along with different working and assembly modes has been introduced in earlier publications. Robot structures designed for this approach are able to change their assembly modes. Using the drives' position feedback systems these assembly modes cannot be distinguished, which is necessary at least after startup of the robot control to correctly solve the structure's kinematic models. In this paper different approaches for a detection of the actual assembly mode of a kinematic structure are presented. Using the example of a Triglide-robot one of the approaches is demonstrated in more detail. It is based on a comparison of measured drive forces, necessary to hold the structure against gravity, with theoretical holding forces, calculated for all possible assembly modes. Experimental results show the effectiveness of the approach.**

I. Introduction

WHILE the advantages of structures based on closed kinematic chains, such as high structural stiffness or low moved masses allowing for high accelerations, are in great demand, there are still drawbacks to these parallel kinematic structures inhibiting a broader use of this promising technology. One of them being the characteristic that the ratio between a structure's workspace and its installation space is usually smaller for parallel kinematic structures than for their serial counterparts.

One way to resolve this problem is the use of several workspaces going along with different solutions to the direct kinematic problem (DKP) and to the inverse kinematic problem (IKP), while usually only one of these workspaces is used. The solutions to the DKP, allowing to calculate the pose (position and orientation) of the endeffector for given drive positions, are also known as assembly modes [1]. Dividing these assembly modes, there are usually singularities of second type, in which an infinitesimally small movement of the endeffector is possible, while all actuators are unmoved [2]. It has been shown though, that under certain conditions a change of assembly mode can be conducted without passing a singularity [3]. On the other hand the solutions to the IKP, providing the necessary drive positions for a desired pose of the robot's endeffector, are known as working modes [1]. They are divided by singularities of first type, which occur when a kinematic chain of the structure is either in a stretched position or the links of the chain are folded upon each other [2]. In such a singular position, at least one actuator can fulfill an infinitesimally small motion without moving the endeffector. Each combination of these working and assembly modes (called configuration here) has a corresponding workspace.

Since these workspaces are typically not identical, the use of several configurations' workspaces allows for an enlargement of the overall workspace, while the installation space can remain unchanged. Thus the ratio of workspace to installation space can be enhanced. To use several workspaces a reconfiguration of the structure is necessary, which was successfully realized in [4] for a planar structure. For spatial structures a similar approach was presented in [5]. In [6] we introduced a spatial Triglide-structure specifically optimized for this kind of workspace enlargement.

To allow for this workspace enlargement approach the structures mentioned above have the ability to change their assembly mode by passing singularities. Hence, for known positions of the drives the endeffector can be in different poses and the mere knowledge about the drives' positions is not sufficient to determine the actual assembly mode. Thus, at least once after startup of a robot's control a determination of the actual assembly mode is necessary. Manually, this can be done in two ways. Either the structure is always moved into a certain configuration before starting the control, which is only possible for manually movable structures. Or the user can visually detect the structure's configuration and feed it into the control. Both ways require user action and are not safe against operating errors. Since the configuration is needed not only for control of the structure's movements, but for many safety functions, such as detection of workspace boundaries due to singularities or self-collisions, a wrong input can lead to severe damage. Thus a method for automatic detection of a structure's configuration is required.

While several authors have addressed the problem of finding the number of real assembly modes for particular parallel kinematic structures [7], [8], there are, to the authors' best knowledge, no works dealing with automatic assembly mode detection without additional sensors for

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parallel kinematic structures. The aim of this paper is to present a systematics on possible approaches for configuration detection. For the most suitable approach based on a comparison of necessary drive forces for different configurations a more detailed description of the necessary procedure is given for a Triglide-robot. Experimental results show the feasibility of the method.

II. Triglide-Robot

A. Prototype

The approaches to detect the current configuration will be introduced by means of a Triglide-structure (see Fig. 1) described in [9], which is based on the well known Linear Delta [10], [11]. The parallel kinematic structure is built up of three kinematic chains each driven by a linear motor. The parallel arrangement chosen for the linear motors is similar to one used for the machine tool Quickstep [12]. Together these chains guide the working platform. Due to the use of two parallel rods for the build-up of each chain the platform is kept at constant orientation, always. The chains allow for a translational movement of the platform with three degrees of freedom (dof). To realize an additional rotation around the z-axis a serial axis is added to the platform. Thus, the complete structure is of a hybrid type, consisting of a parallel part and a serial part. Its four dof make the classical Scara-motions possible, which are necessary for the better part of handling and assembly operations. Since the serial axis is not relevant for detecting the robot's actual configuration it is neglected in the following. Hence, only the position of the endeffector has to be considered.

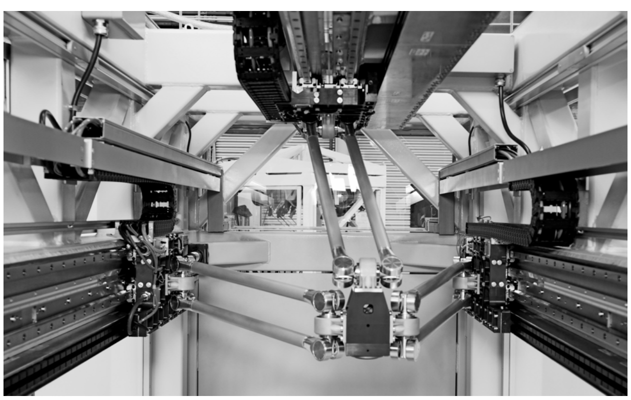

Fig. 1. Prototype of Triglide-robot.

B. Workspace Enlargement

As explained above, each combination of working and assembly modes has a corresponding workspace. For the Triglide-structure Fig. 2 shows the two largest of these configuration workspaces, which will actually be used for working and thus their corresponding configurations will be called working-configurations. If it is possible to change between these two a resulting overall workspace can be achieved also shown in Fig. 2. To accomplish this change several other configuration workspaces and the separating singularities have to be passed. These configurations will be called transition configurations here. For first type singularities such a passing can be managed easily using joint space interpolation. But the passing of singularities of second type, which separate different assembly modes of this structure, needs special considerations, since the platform's position cannot be controlled by the drives in such a singularity. To overcome this problem we proposed an approach using gravity [6] to impose a defined movement on the platform while being in the singularity. Since one of the drives is controlled to exert zero force while passing the singularity and due to the fact that no kinematic models have to be solved throughout this process, the robot's control is kept free of any critical states. The necessary steps and an adapted control strategy for one possible way of realizing this approach are given in [13].

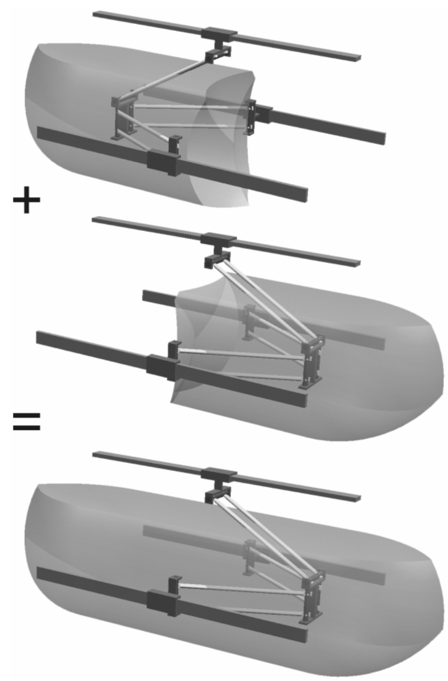

Fig. 2. Largest configuration workspaces and resulting overall workspace for Triglide-structure.

Due to the time necessary for such a change between workspaces it will not be efficient to conduct this transition in every motion cycle. But it is well suited for tasks, which only require an occasional configuration change. E.g. it is reasonable to use this kind of workspace enlargement for robots handling parts from two feeders. Or it is possible to position peripheral devices, such as automatic tooling systems, in one workspace, while working in the other one. It is also very important to mention that the two used configuration workspaces itself contain no further singularities of the second type.

III. Possible Configurations for Triglide-Structure

The amount of possible configurations for the Triglide-structure results from the following considerations: For a given position of the platform there are two possible positions of the carriage in each of the three kinematic chains (i = {1, 2, 3}), which will be denoted as $k_{IKP,i} = \{-1, +1\}$. And for a given set of drive positions there are two possibilities for the position of the endeffector denoted as $k_{DKP} = \{-1, +1\}$, respectively. These two possibilities result from the solution of the DKP, which can be derived analytically by finding the intersection of three spherical surfaces [14] to which there are generally two solutions. Thus a configuration can be described using the vector $\boldsymbol{k} = (k_{IKP,1}\ k_{IKP,2}\ k_{IKP,3}\ k_{DKP})^T$. From the combination of all possible working and assembly modes $2^4 = 16$ different configurations can be derived of which only 14 are physically existent. The two working-configurations of which the workspaces are shown in Fig. 2 are thus denoted as $(-1\ -1\ -1\ +1)^T$ and $(+1\ +1\ +1\ -1)^T$.

Due to the parallel arrangement of the linear motors the shape of workspaces and the structure's kinematic characteristics are independent of the endeffector's position along the x-axis (parallel to linear guides, see Fig. 3 a). Only at the end of the workspaces' x-extension the workspaces' shapes are changed owing to the limitation of the linear drives' moving ranges. Thus characteristics in Cartesian workspaces can conveniently be displayed in cross-sections of the workspaces parallel to the robot's y-z-plane.

Fig. 3 shows workspace cross-sections of such kind. One of the working-configurations (denoted by its configuration $\boldsymbol{k}$) can be seen in Fig. 3 b with its corresponding workspace. As can be seen it is not constricted by any singularity of second type. For transition configurations (Fig. 3 c and d) the workspaces of two configurations differing in their assembly mode are divided by a singularity of second type. The three cross-sections shown sufficiently describe all configurations' workspaces. For all configurations not shown the cross-sections are either the same or symmetrically to the robot's x-z-plane. For a better understanding it should be mentioned, that the upper boundaries of the shown workspaces have no kinematic origin. The robot's workspace has been limited in z-direction throughout the design process to avoid a cantilevered design of the upper carriage, which would result in higher moved masses.

The aim of this work is to detect the unknown configuration of the robot's structure. To get an impression on the number of configurations out of the total of 14 that can exist for a certain position of the endeffector the following analysis has been conducted: The robots overall Cartesian workspace is discretized with a fine grid. For every Cartesian position it is attempted to solve the IKP for all possible (eight in total) working modes. For all real solutions the assembly mode is determined. This is done by solving the DKP for both possible configurations using the drive positions resulting from each IKP-solution and comparing the results to the original Cartesian position. The number of possible configurations for each examined Cartesian position is shown in Fig. 4 exemplarily for a cross-section through the overall workspace parallel to the robot's x-z-plane. The cross-section is located at y = 0, which is the middle of the workspace. The results show, that for an area in the middle of the cross-section a maximum of eight different configurations can exist for one single endeffector position. This goes along with the maximum number of working modes, since the two possible solutions of the DKP for one working mode cannot result in the same endeffector position (except in singularities of second type). It can also be seen, that for two large areas of the workspace's cross-section only one configuration is possible, respectively. These areas are part of the two working-configurations.

IV. Assembly Mode Detection

Generally, when the control of a robot with the ability of assembly mode change is started, all configuration

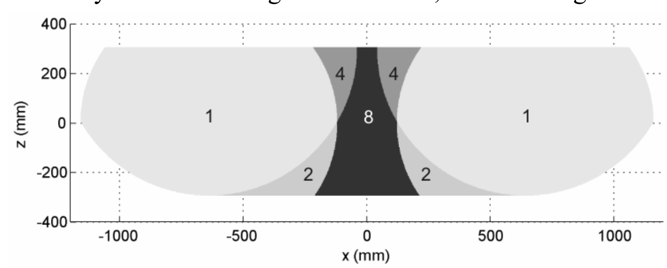

Fig. 4. Possible number of working modes in workspace cross-section parallel to x-z-plane (y = 0).

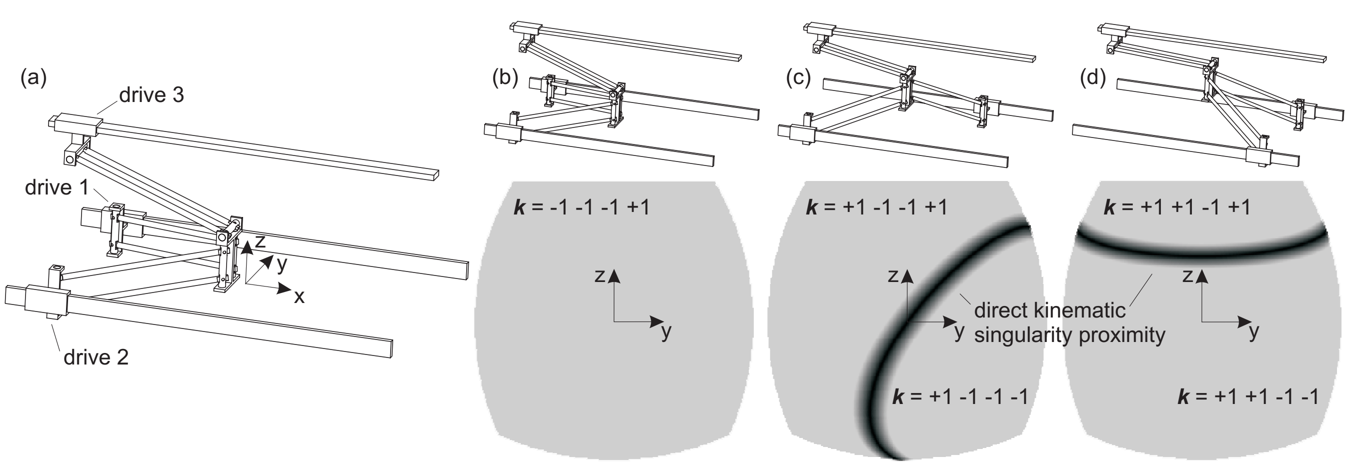

Fig. 3. Kinematic structure (a) in different configurations (b - d) with corresponding cross-sections of workspaces parallel to robot's y-z-plane.

parameters of IKP and DKP are unknown. Thus, it is not possible to calculate the actual position of the endeffector for known drive positions. These drive positions are either already known at startup, if the drives are equipped with absolute feedback systems, or have to be determined using a reference-run, if incremental feedback systems are used. The main problem at hand is the determination of the assembly mode. Once it is known together with the drive positions, the working mode can easily be determined, as we will show later on.

Focusing at first on the assembly mode detection we shortly examine in the following six general approaches (A - F) listed in Fig. 5. They are categorized by the employed state of motion of the kinematic structure and by the necessity of additional sensors besides the ones used in the drives. These categories are based on the following considerations: To keep additional costs for the assembly mode detection low, it is favorable not to be dependent on any additional sensors. In the drives usually several signals are already measured for robot control. For safety reasons it is preferable, that the robot's structure does not have to be moved to determine the assembly mode, because additional effort is necessary to avoid any collisions during these moves.

		Structure's State of Motion	
		Fixed	Moving
Sensors	in Drives	A. Comparison of Static Holding Forces	B. Comparison of Dynamic Drive Forces C. Drive Movement due to Falling of Structure
	in/on Structure	D. DKP with Sensor-Redundancy E. Direct Assembly Mode Detection	F. Use of Sensors for Dynamic Effects

Fig. 5. Different approaches for assembly mode detection.

A. Comparison of Static Holding Forces

Together with approach B (see Fig. 5) this approach is based on the forces (or torques) applied by the drives. For many electrical drives these values are measured (by means of the drive currents) for control purposes, anyway. A requirement for this approach is that the influence of gravity on the masses of the kinematic structure makes an action of the drives necessary even to statically hold the structure in place. This feedback of gravity on the drive forces must not be obstructed by high gear ratios or high friction. The main idea of the approach is, that these drive forces needed to hold the structure may differ for the different assembly modes, that are possible for the actual position of the drives. Exemplarily this is shown in Fig. 6 using the Triglide-structure. For a set of drive positions both possible assembly modes are pictured and the drive forces necessary to hold the structure in place against gravity are displayed qualitatively.

A second prerequisite is the existence of a dynamic model

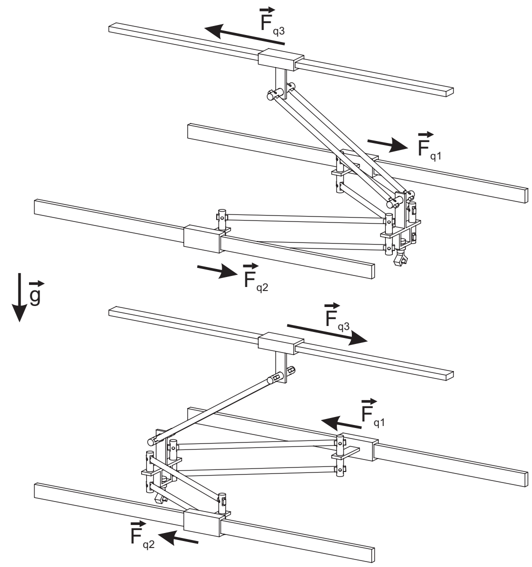

Fig. 6. Drive forces to hold the Triglide-structure against gravity for both possible assembly modes.

calculating the necessary drive forces for a given drive position. This model should accept as an input a configuration parameter denoting the assembly mode, for which the model is to be solved. Using this model the drive forces necessary to hold the structure against gravity in all assembly modes possible for the actual drive positions can be calculated. These values can be compared with measured drive forces for the actual assembly mode and thus the assembly mode can be determined. This is only possible, if the force-difference for the different assembly modes is (at least for one of the drives) high enough. Especially it has to be two times higher than the largest error between measured and calculated drive forces for the same assembly mode. That way measured values can be unambiguously related to the calculated values of one assembly mode. The named errors can be due to an insufficiently accurate modeling or due to measurement noise.

B. Comparison of Dynamic Drive Forces

Instead of drive forces necessary to statically hold the structure in place this approach uses drive forces applied to dynamically move the structure. Thus, it is not necessary to have an influence of gravity on drive forces. Instead the fact is used, that the transmission ratio between an acceleration of the drives and the resulting acceleration of the endeffector may be different for several assembly modes. As a result the drive forces necessary for a given movement of one or more drives can vary.

Again, a dynamic model is needed, calculating the drive forces for a given drive movement with regard to a given assembly mode. It can be used to compare the theoretical drive forces for a given joint-space test-trajectory with measured forces. The main task is to find a test-trajectory causing a big enough difference in the drive forces for the different assembly modes while at the same time ensuring a safe motion of the structure for all possible assembly modes.

The drive forces at least need to be compared for special moments of the trajectory (e.g. moment of highest drive acceleration).

C. Drive Movement due to Falling of Structure

This variant of assembly mode detection is again based on the effects of gravity. It is applicable, if the influence of gravity on the endeffector is much larger than its influence on the drives (e.g. if the inertia of the drives is small compared to that of the endeffector, or if the vector of gravity is perpendicular to the stroke of linear drives). If a structure is allowed to fall (e.g. by releasing one of the drives) under such conditions part of its endeffector's direction of motion will always point in the direction of gravity. Additionally, the fact is used, that the resulting direction of movement of the released drive may differ depending on the actual assembly mode. In Fig. 7 this is shown for the-Triglide structure. Note that the movement of the released upper drive is displayed exaggeratedly to show the effect. In practice very small movements are sufficient, that allow for a detection of the direction of movement.

To use this effect for assembly mode detection we start with an unmoving state of the structure and a known position of the drives. Now one of the drives is allowed to move (without applying any force or torque) for a short time. This will cause the structure to fall a little bit, causing the released drive to move. After coming to a stop again, the position of the drives is determined again. For both sets of drive positions (before and after the fall) the endeffector position can be calculated using the DKP. By comparing these positions it can be determined whether the endeffector has moved in the direction of gravity or not. These calculations can be done for all possible assembly modes, allowing to find the actual one, for which the endeffector has moved in the direction of gravity.

Even if only two assembly modes are to be distinguished, this approach does not have to be unambiguous for all positions in a structure's workspace. Thus it has to be checked for each set of possible drive positions, that for at least one drive - if released for a short time - the resulting direction of drive movement is different in both possible assembly modes. By releasing this drive the assembly mode can be determined unambiguously. To determine, in which direction a drive will move (in a certain assembly mode) a dynamic model can be used. The sign of a drive's force needed to hold the structure statically in place gives information about the direction this drive would move in, if it was released. The calculated drive force can even be used to determine, that the force exerted by the structure on this drive is large enough to move it against friction in the driven joint.

D. DKP-Solution with Sensor-Redundancy

Using additional sensors measuring the actual position/angle of passive joints in a structure it is possible to analytically calculate the endeffector's actual pose for actual drive positions even for structures for which the DKP-solution normally requires numerical methods. This has been shown in many publications, e.g. by Merlet [15]. Such calculations make it superfluous to determine a structure's assembly mode. Since this method requires several additional sensors of high resolution, which add to the cost and moved masses of the machine, it is only mentioned for the sake of completeness.

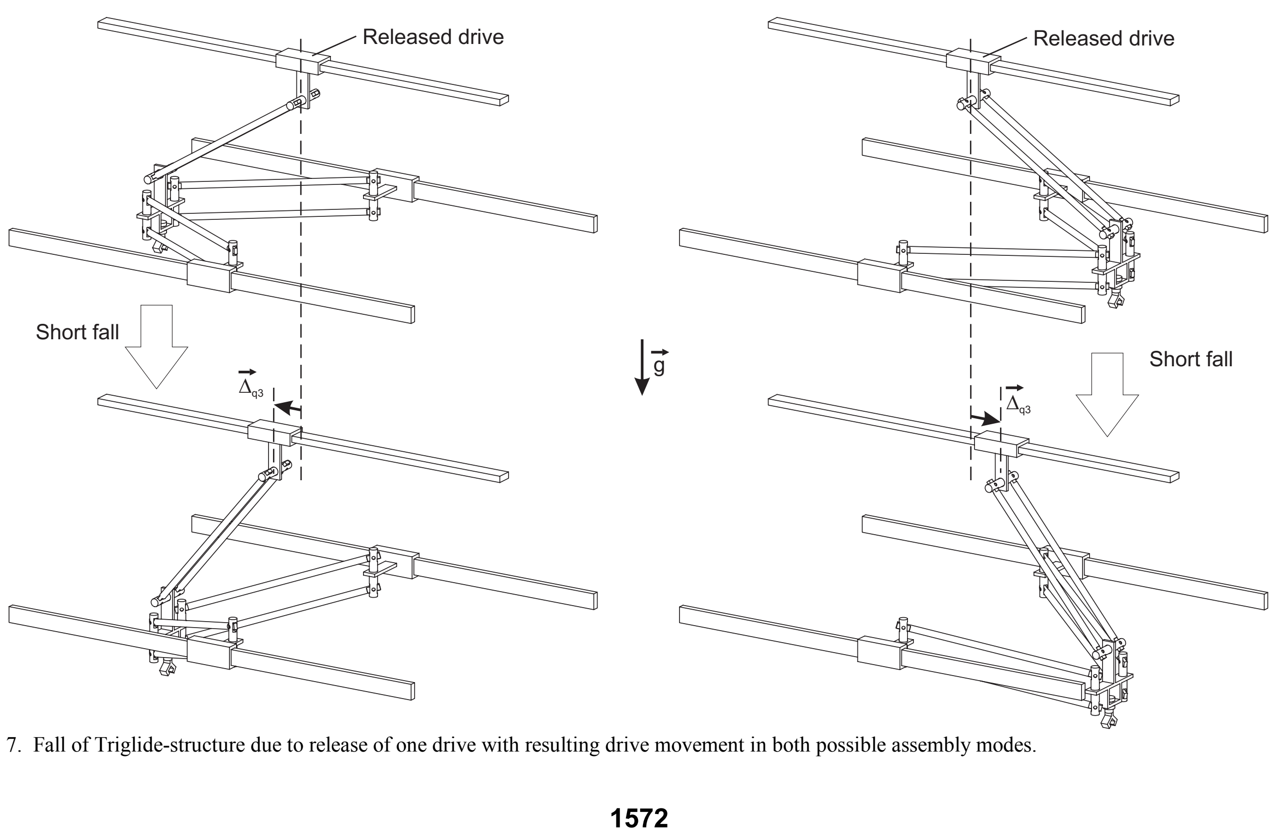

Fig. 7. Fall of Triglide-structure due to release of one drive with resulting drive movement in both possible assembly modes.

E. Direct Assembly Mode Detection

But with some simple structures even more basic sensors can be used. This is the case, for example, for the planar PRRRP-structure, for which the above mentioned workspace enlargement approach was implemented [4]. Here, the singularity of second type, separating two assembly modes, is characterized by a parallel alignment of the two connected links 1 and 2 shown in Fig. 8. Thus two angular ranges of the passive joint angle ε in point E can be unambiguously related to two assembly modes, which can be easily detected using a simple proximity switch.

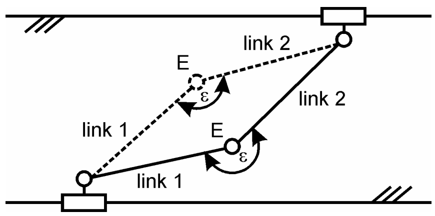

Fig. 8. PRRRP-structure in two assembly modes.

F. Use of Additional Sensors for Dynamic Effects

One last approach is based on additional sensors on the structure, measuring dynamic effects. The most simple option is the use of an accelerometer on the working platform. As in approach B the fact is used, that the acceleration of the endeffector resulting from a given acceleration of the drives can be different for several assembly modes. In this case a model is needed supplying the acceleration at the position of the accelerometer depending on a given movement of the drives (for all possible assembly modes). Again, the theoretical values for all assembly modes can be compared to the measured values for a test-trajectory with the same requirements as in approach B.

V. Assembly Mode Detection for the Triglide using Static Holding Forces

For the Triglide-robot we choose approach A using static holding forces for the detection of the actual assembly mode. Since no additional sensors and no movement of the robot are necessary, it is the most appropriate approach. It can be used, since the influence of gravity on this spatial structure makes drive forces necessary for static holding of the structure. Given that direct electric drives with no additional gears are used in the design a direct feedback from gravitational forces on the structure on the drive forces can be expected. As the amplifiers for these drives measure the drive currents (which are approximately proportional to the forces) for their current control loop, no additional sensors are necessary. For computation of the necessary theoretical drive forces a dynamic model is applied originally derived for the computed-torque feedforward control approach, which is used for this robot. The model is based on Jourdain's Principle, balancing virtual powers. For a given movement of the drives (position, velocity, acceleration) the necessary drive forces can be determined with respect to the DKP-configuration k_{DKP}.

A. Check for Applicability

To check whether the approach is applicable, it has to be determined that the theoretical difference between the drive forces (of at least one drive) for both possible assembly modes is larger than model or measurement errors for all (or at least most) drive positions possible in joint space. Since presentation of characteristic values for a joint space workspace is hard to grasp for most people having the Cartesian workspace in mind, the following simulation will include an additional step, allowing for a presentation in Cartesian space.

After discretizing a cross-section of the workspace parallel to the robot's y-z-plane with a rectangular grid, the IKP is solved for each endeffector position using a chosen working mode resulting in the related drive positions. For each set of drive positions the static holding forces are calculated for both possible assembly modes (one of them leading to the original endeffector position, the other one being related to an endeffector position somewhere else in Cartesian space). For each position the drive with the highest absolute difference of both forces is determined. Subsequently its force difference values are plotted over the y-z-cross-section of the workspace. Fig. 9 shows these plots for the three working modes introduced in Fig. 3.

This force difference between the theoretical holding forces helps us to unambiguously relate a measured force to one of them. In case of a perfect model and perfect force measurement a very small difference would be sufficient. But in the presence of model inaccuracies and measurement errors a higher difference is needed for the approach to be functional. Since the necessary difference is dependent on the accordance of modeled and measured forces, it has to be evaluated experimentally. For that, the endeffector of the Triglide-robot is moved to different positions in the workspace consecutively. In each position the robot is stopped and the static holding forces are measured over 1 s. For all positions and all drives the maximum of the absolute difference between the (filtered) measured forces and the corresponding theoretical holding forces is determined. This value computes to 26 N for the prototype. The necessary force difference for the above simulation has to be at least double that value, so a value of 60 N is chosen.

The static holding forces considered here are dependent on the mass of the moved parts of the structure. Since smaller forces are necessary to hold smaller masses against gravity, the minimum possible weight of the Triglide-structure has been used to be on the safe side. Thus, no payload has been applied in the described simulations and experiment.

As can be seen in Fig. 9 all configurations feature a force difference easily high enough for the determination of the assembly mode in nearly all parts of their workspaces.

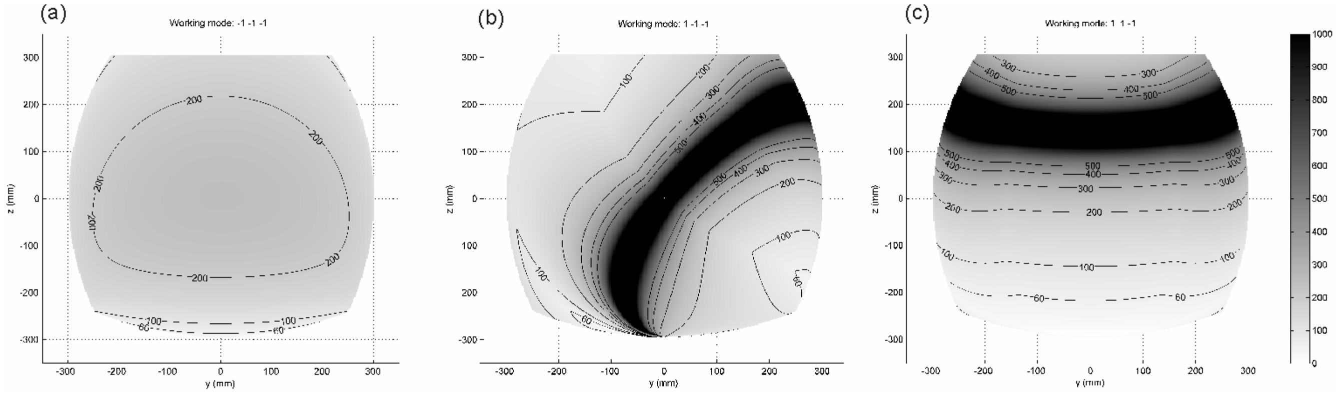

Fig. 9. Absolute difference in static holding forces (N) of relevant drive for both possible assembly modes.

Especially in the working configurations (see Fig. 9 a), in which the robot is normally used and thus shut off and restarted, only 0.7 % of the workspace cross-section do not allow for the application of the configuration detection algorithm. In the transition configurations (Fig. 9 b and c), which are only used for changing the assembly mode, these regions are a little larger. In these cases either the algorithm can be stopped or the platform can be moved to a different position, where the algorithm can be started again. Since these regions affect only a small part of the workspace, the approach is generally applicable for the Triglide-robot.

B. *Implementation*

Due to the use of incremental encoders as a feedback system for the Triglide's linear drives the drives' positions are not known at startup, which makes a reference run necessary. Using distance-coded reference marks a drive movement of 80 mm is sufficient for referencing. By moving all three drives synchronously at constant speed it is ensured that the endeffector does not move in y- or z-direction, which could move it closer to a singularity of second type.

After referencing the following procedure is used to determine the structure's actual assembly mode:

- Determination of static holding forces: Drives are position controlled for 1 s with desired values equal to actual values while the brakes are released (The brakes hold the structure against gravity, if the drives are disabled). The force signals are filtered calculating a running average over 50 samples (taken every 1 ms).
- Use actual drive positions to calculate theoretical static holding forces for both assembly modes.
- Determine drive *p* with largest difference between both forces.
- Check whether force difference for drive *p* is above 60 N. If not the algorithm is terminated with an error message to the user (Alternatively, the endeffector can be moved to a different position. This can be done easiest by moving drive 3 for a short distance (e.g. 20 mm) while supervising the workspace for both possible assembly modes. After the movement the algorithm is restarted.).
- Compute absolute differences between measured holding force for drive *p* and theoretical holding forces for both assembly modes. The smaller difference indicates the actual assembly mode.

After determination of the assembly mode the working modes can easily be identified using the following procedure:

- Calculate the actual position by solving the DKP for the actual drive positions and the known assembly mode.
- Solve the IKP for all possible working modes: $(\boldsymbol{k}_{IKP})_m^T = \{(-1\ -1\ -1); (-1\ -1\ +1); (-1\ +1\ -1); (-1\ +1\ +1); (+1\ -1\ -1); (+1\ -1\ +1); (+1\ +1\ -1); (+1\ +1\ +1)\}$
- Compare each solution with the actual drive positions. If the largest absolute difference for all drives is smaller than a set limit (e.g. 1 µm) the working mode is marked as actual working mode (If more than one working mode is marked as actual one of the structure's chains is within a singularity of first type, in which case the algorithm can be terminated. Alternatively, the drive of this chain can be moved for a short distance (e.g. 1 mm), after which the algorithm can be restarted).

After successful computation of these procedures the actual working and assembly modes are known. Thus all kinematic and dynamic models of the robot can be solved unambiguously, making a safe robot operation possible.

VI. Experimental Results

To deliver insight into the practical realization the configuration detection procedure is applied for different drive positions and different configurations of the structure, resulting in different Cartesian endeffector positions (see Table I). In these positions the endeffector is held in place statically by the drives. Fig. 10 shows the essential measured and calculated forces needed for configuration detection: For each endeffector position, the calculated theoretical holding forces of drive *p* are given for both possible assembly modes. Additionally, the measured and filtered force of the same drive is given. The values measured in the drives' controllers are read by the robot's control once every millisecond. The signal is filtered calculating a running average over 50 samples. As can be seen the signal quality is sufficient to unambiguously relate the measured signal (at any time) to the theoretical holding force of the actual DKP-configuration given in Table I, which allows for assembly mode detection. This applies for positions a) and b) in the

TABLE I
DRIVE POSITIONS (q1, q2, q3), CONFIGURATIONS AND RESULTING ENDEFFECTOR POSITIONS USED FOR MEASUREMENTS

	q1 (mm)	q2 (mm)	q3 (mm)	x (mm)	y (mm)	z (mm)	$\boldsymbol{k_{IKP}}$	k_{DKP}
(a)	0	0	0	519.592	0	4.959	–1 –1 –1	+1
(b)	0	0	0	-519.592	0	4.959	+1 +1 +1	–1
(c)	-161	33	39	400.316	150.129	-149.876	–1 –1 –1	+1
(d)	-161	33	39	-524.477	-148.888	162.432	+1 +1 +1	–1
(e)	367	-561	-560	0.072	-150.138	150.797	+1 –1 –1	+1
(f)	367	-561	-560	-195.905	152.973	-146.701	+1 –1 –1	–1
(g)	206	-531	-564	0.056	-199.673	260.603	+1 –1 –1	+1
(h)	206	-531	-564	-353.990	235.213	-205.461	+1 –1 –1	–1

middle of the working configurations' workspaces with a high difference of about 250 N between the theoretical holding forces as well as for positions g) and h) very close to a transition configurations' workspace boundary with a force difference of only 81 N.

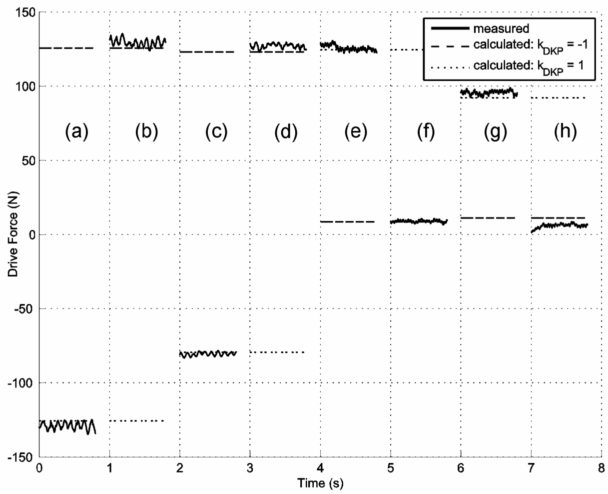

Fig. 10. Measured static holding forces in different endeffector positions with corresponding theoretical holding forces in both assembly modes (for drive *p* with largest absolute difference of theoretical forces).

VII. CONCLUSION

If kinematics and design of a robot based on a parallel kinematics structure allow for a change of its assembly mode without disassembling the structure, an automatic detection of the actual assembly mode is needed after startup of the robot's control to be able to correctly calculate kinematic or dynamic models. Six different approaches, applicable for different types of structures or boundary conditions (e.g. influence of gravity on the structure), were presented throughout this paper. Finally one of them was chosen for the Triglide-robot used as an example in this paper.

The experimental results together with the results from the applicability check in chapter V show that using the demonstrated comparison of static holding forces the configuration of the Triglide-structure can effectively be detected. Thus, for this structure with its ability to change its configuration a safe startup procedure is possible, making the implemented workspace enlargement approach even more effective.

Currently this method is expanded to be functional even if the value of the payload attached to the endeffector is unknown to the dynamic model used in the approach.

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