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Adaptronic Joints Based on Quasi-Statical Clearance Adjustment as a Means to Improve Performance of Parallel Robots

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ABSTRACT

Robots based on parallel kinematics feature low moved masses, allowing for better dynamic performance compared to serial mechanisms. Otherwise, the known drawbacks, like occurrence of singularities or bad ratio of work space to installation area, hinder their full industrial establishment. In order to overcome some of these drawbacks, development of specific and optimized robot components, like rods or joints, becomes necessary. In this work, development of passive joints with integrated piezo-actuators (adaptronic joints) is discussed. To deal with these complex issues this paper focuses on three major areas: firstly, conventional joint concepts, including their main flaws; secondly, new, adaptronic joint concepts based on quasi-statical clearance adjustment including two laboratory prototypes and their improvements over the old solutions; thirdly and finally, discussion about possible improvement of the overall performance of parallel robots by using new developed joints. By drawing on experimental results derived from laboratory tests, it is possible to show how implementation of the developed joint prototypes could influence friction characteristic of the whole robot system.

Keywords: Parallel Robot, Adaptronic Joint, Clearance Adjustment

1. INTRODUCTION

Parallel kinematic structures based on closed kinematic chains have some remarkable advantages compared to serial mechanisms. Since their drives are not moveable (mainly mounted on the rack) they are characterized by low moved mass and high stiffness, which allow high velocity and high acceleration. Exploiting this advantage, some parallel kinematic structures have already been implemented in application fields such as handling and assembly, manufacturing, motion simulation, etc. Beside the mentioned advantages there are also some disadvantages of the parallel structures which hinder their full industrial establishment. The most important are occurrence of the singularities within the work space or bad ratio of the work space to the installation area.

In order to overcome these drawbacks, different strategies are used. The first and most important step is a systematic structure synthesis [1]. Moreover, strategies for the structure modularization play a very important role in order to offer more alternatives and improve development flexibility [2]. Some of the more advanced approaches are development according to the appropriate application (task) [3] and/or appropriate requirements [4]. In order to capitalize on advantages of the defined structure, its parameters have to be optimized. Since the correlations between them are mostly not explicit, the only solution is a multi-criterion optimization (Pareto-optimization) [5]. Since the structure is modularized and optimized according to different criteria, development of adequate structure components becomes necessary. Within the Collaborative Research Centre 562 “Robotic Systems for Handling and Assembly” in Braunschweig, Germany, different possibilities for improvement of the overall structure performance by specifically developed components have been tested and verified. For example, for improvement of the structure damping performance, adaptive rods (rods made from carbon fibre with embedded piezoceramic actuators) are implemented. They can oscillate against the operational excitation and suppress vibrations in the structure [6].

Beside the rods, joints are also components which are very important for achievement of the overall performance of parallel robots. They connect different structure components, enable relative movement between them and thus determine and influence behaviour of the whole robot system.

2. CONVENTIONAL PASSIVE JOINTS FOR PARALLEL ROBOTS

The available commercial joint solutions (e.g. from INA-Schaeffler KG, Hephaist SEIKO Co. Ltd. [7]) are primarily designed for parallel kinematic machine tools. They are too big and heavy and therefore not adequate for application in parallel robots. Other available solutions are mostly developed together with appropriate structures so that they cannot be of universal importance. Therefore development of a general methodology for the development of passive joints for parallel robots becomes necessary.

The first methodology for systematic development of passive joints for parallel robots was proposed by Otremba [7]. Based on this methodology joints for diverse parallel structures with one or more degrees of freedom (DoF) have been developed and tested [7]. In order to upgrade the developed joints, different strategies (integration of micro-fabricated sensors [8] or adaptronic components in the joints) can be used. In this work integration of adaptronic components in the joints for an optimal adjustment to different operating conditions is discussed.

3. INTEGRATION OF ADAPTRONIC COMPONENTS IN PASSIVE JOINTS FOR PARALLEL ROBOTS

The aim of the integration of adaptronic components in the joints is development of adaptive joints which can actively suit different operating conditions (in different operation modes requirements on joints are different – fast movement of the robot demands no friction in the joints, for slowing down high friction/damping is necessary and while assembling it shouldn’t be any clearance in the joints because of preferable high precision). In that way clearance and friction in joints can be influenced so that solutions for concurrent goals can be found. In articles from Pavlovic et al. [9, 10] two different working principles for achievement of the active adaptability are presented: high-frequency excitation, where interacting friction surfaces oscillate with high speed relatively to each other and quasi-statical clearance adjustment, where the clearance and hence the forces between the friction surfaces are adjusted slowly (e.g. once per robot task). In this paper further development of the joints based on the second working principle is discussed.

3-1. Adaptronic joints based on quasi-statical clearance adjusment

According to the design methodology presented in [9], a function structure for adaptronic revolute joints based on quasi-statical clearance adjustment can be established (Figure 1).

Initial point is a general definition of the joint as a link between two other structure components. Beside the linking function, a joint enables transfer of mechanical and kinetic energy between other structure components.

In order to achieve adaptive clearance adjustment in the joint, some additional sub-functions have to be added. Since the clearance adjustment is realized by adaptronic components (multifunctional materials), transformation of electrical into mechanical energy takes place. The transformed mechanical energy is transmitted further to the bearing where the clearance is adjusted. Depending on the selected actuator and achievable force/stroke, it is sometimes necessary to realize transmission magnification or transmission reduction.

For the control of the described "mechanical part" of the joint (sub-functions framed in the lower rectangle in Figure 1), a control unit is necessary (upper rectangle in Figure 1). The control function is also divided in several different sub-functions: friction measurement, measured values amplifying, target-actual value comparison and energy set-up. In this work only solutions where control takes place outside of the joint (integrated in the drive – virtual sensing principle) are discussed. Future development of adaptronic joints will show, whether an eventual integration of the control unit in the mechanical part of the joint is possible, in order to achieve a more compact solution, i.e. an intelligent joint.

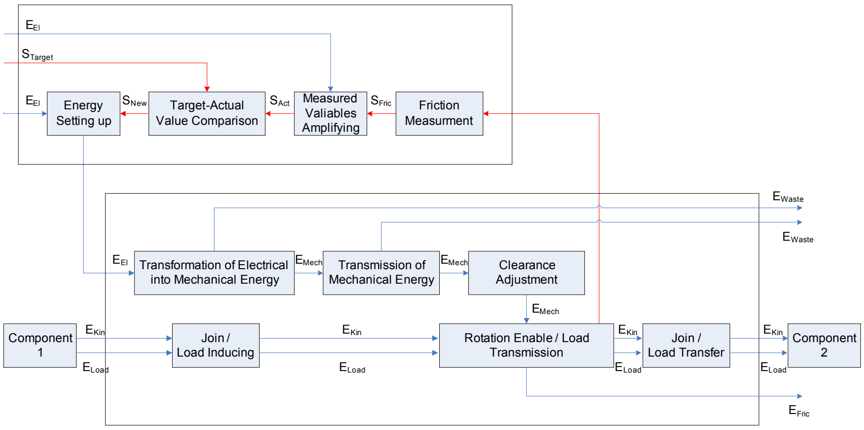


Figure 1. Function structure for adaptronic revolute joints based on quasi-statical clearance adjustment

Using different variation methods [11] and available design catalogues [12] it is possible to find different physical and appropriate working principles for each sub-function described in Figure 1. By their combining different concepts of adaptronic joints can be developed [9]. Based on the variety of possible solutions different laboratory prototypes of revolute adaptronic joints are realized.

3-2. Laboratory joint prototypes

In the laboratory joint prototypes shown in Figures 2(a) and 2(b), clearance between friction surfaces of integrated plain (Figure 2(a)) and rolling bearings (Figure 2(b)) is changed by varying the length of integrated actuators. Thereby the generated actuator force causes a higher normal force in the friction surfaces and thus a higher friction. Using combined axial-radial bearings, clearance in both directions can be influenced simultaneously.

The joint prototypes consist of a central ring (1), which is fixed with six screws (4) between the upper (2) and the lower (3) part of the test bench housing. On both sides of the ring, two high voltage (1000 V) piezo ring actuators (5) are fastened. They are 18 mm long and have an outside diameter of 35 mm and inside diameter of 25 mm. In a no-load condition they can realise a stroke between 17-25 μm at a stiffness of 1000 N/μm. Thereby the maximal generated force amounts to 20000 N. On the front surfaces of the piezo rings, two washers (6) are fastened. They rest against the outer ring of the angular contact spherical plain bearings (7a) or tapered roller bearings (7b) which have shaft diameter of 25 mm. The inner rings of the bearings are blocked with the shaft shoulders (8) and the necessary pre-stressing of the bearings is realised by a slotted round nut (9).

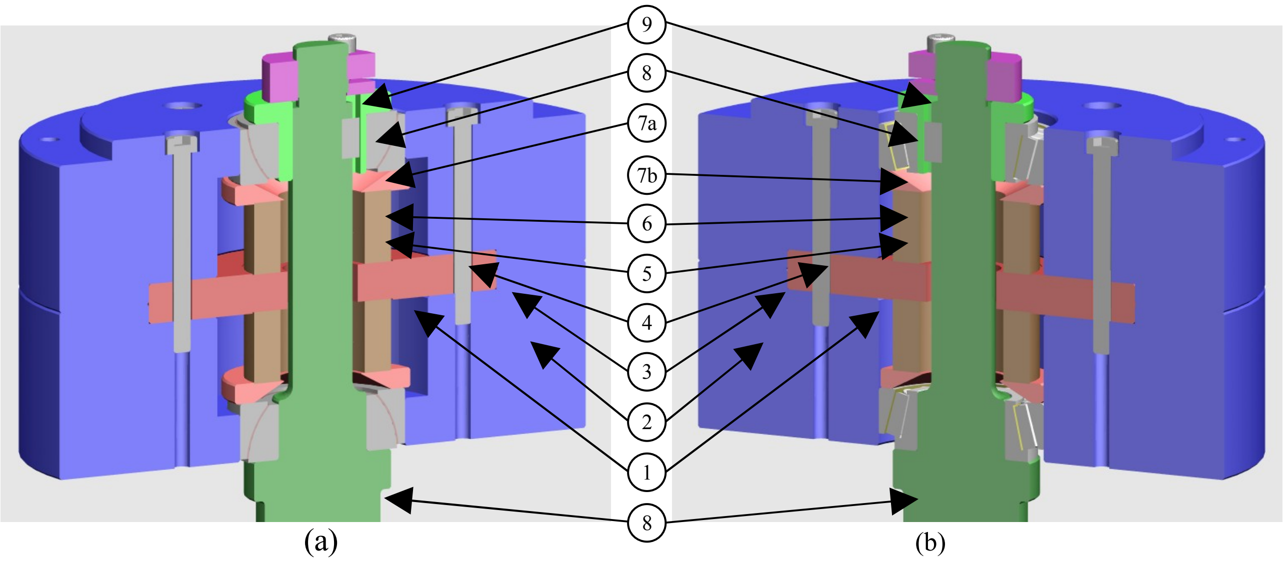


Figure 2. Laboratory joint prototypes with integrated plain (a) and rolling (b) bearings

In initial position there is a clearance between friction surfaces in the bearings. If the piezoceramic actuators are activated, they shift the outer rings of the bearings over the washers. Since the inner rings of the bearings are blocked, the clearance is decreased. With deactivation of the actuators outer rings of the bearings return to their initial position and the predefined clearance is restored. In this way different clearances can be continuously adjusted and therefore different friction moments can be achieved.

4. EXPERIMENTAL INVESTIGATIONS

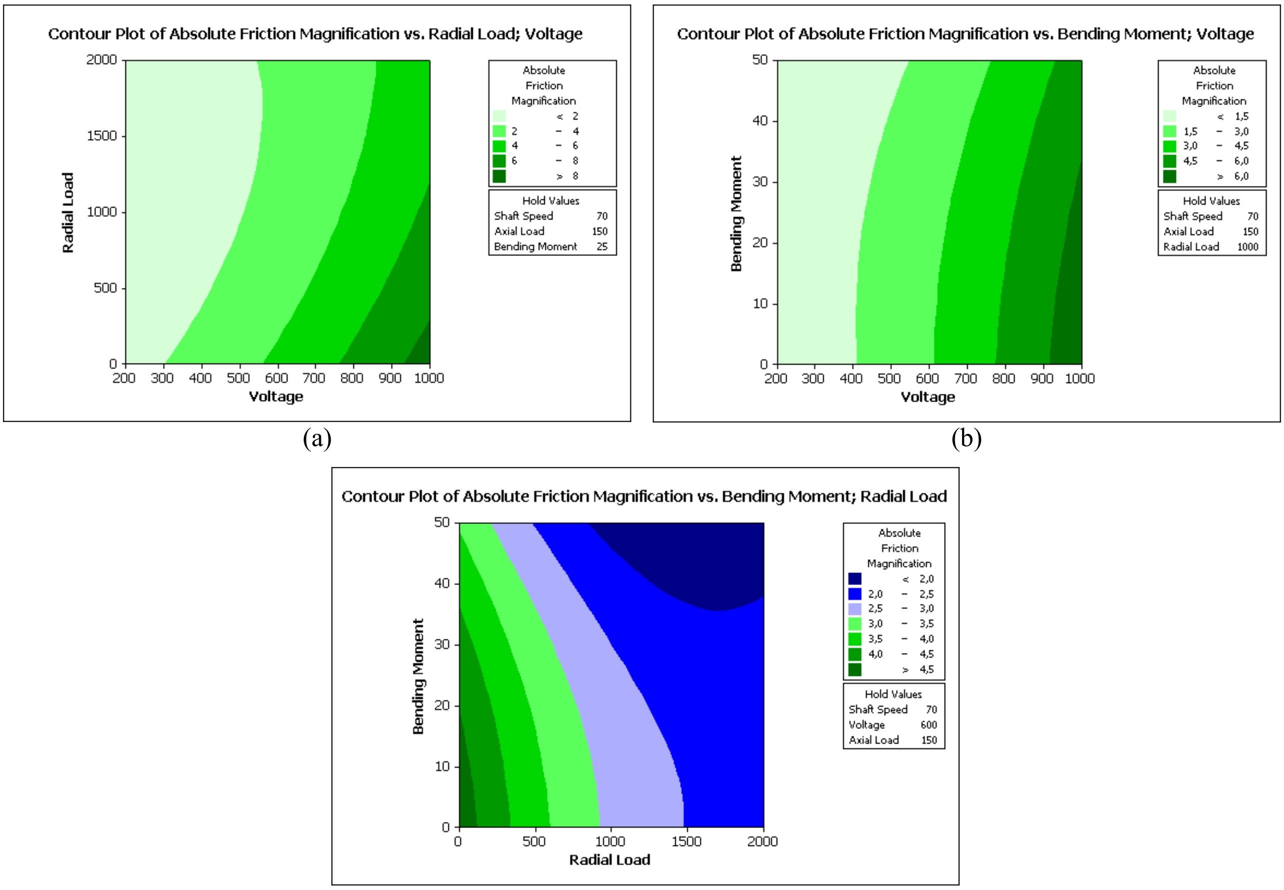
Some of the experimental results of the laboratory joint prototypes are presented in [13, 14]. In [13] it is shown that the friction magnification as well as the joint blocking by using piezoceramic actuators is possible. On the other side in [14] it is shown how the relative friction magnification (ratio between friction in the joint with and without using piezo-actuators) depends on different parameters. In this work absolute friction magnification as well as differences between absolute and relative friction magnification are discussed.

4-1. Methodology

Using the same methodology as in [14] influence of the following five parameters on the friction magnification is discussed: shaft speed, applied voltage, axial load, radial load and bending moment. The speed profile was typical for parallel robots for handling and assembly (pick & place task) with speed values between 20 and 120 rpm. The applied voltage varied from 200 V to 1000 V. In order to simulate real operating conditions, influence of different load types (axially, radially, bending) were investigated. Axial load took values from 0 to 300 N, radial load from 0 to 2000 N and bending moment from 0 to 50 Nm. The plain bearings were pre-stressed so that friction moment in the unloaded joint was about 8 Nm (recommended value by bearing manufacturer is between 7 and 9 Nm) and rolling bearings were prestressed so that friction moment corresponded to the recommendations of bearing manufacturer (about 0,5 Nm). The tests were carried out with an in-house test bench [9, 10] which enables measurement of the friction moment in the prototypes.

4-2. Results

Test results for the joint with plain bearings show that the absolute friction magnification (difference between friction in the joint with and without using piezo-actuators) in the investigated range depends significant on voltage, radial load and bending moment (Figure 3). Dependence of the friction magnification on the applied voltage is directly proportional (see plots (a) and (b)). That is expected because higher voltage induces bigger stroke of the actuators and therefore higher normal force in the bearings. Dependence between radial load and friction magnification is reciprocal (see plots (a) and (c)) because of the integrated plain bearings. In this type of bearings friction increasing which is caused by radial load is smaller at higher than at lower axial loads. Since the force induced by actuators is equivalent axial load for the bearings, influence of the radial load falls off when the actuators are activated. The applied bending moment in the joint is mechanically equivalent to radial load, so as a matter of course its influence is also reciprocal (see plots (b) and (c)). In the investigated range radial load is more significant than bending moment and has the same importance as the actuator. Compared to the relative friction magnification which is presented in [14], there is no difference in order to significant influences.

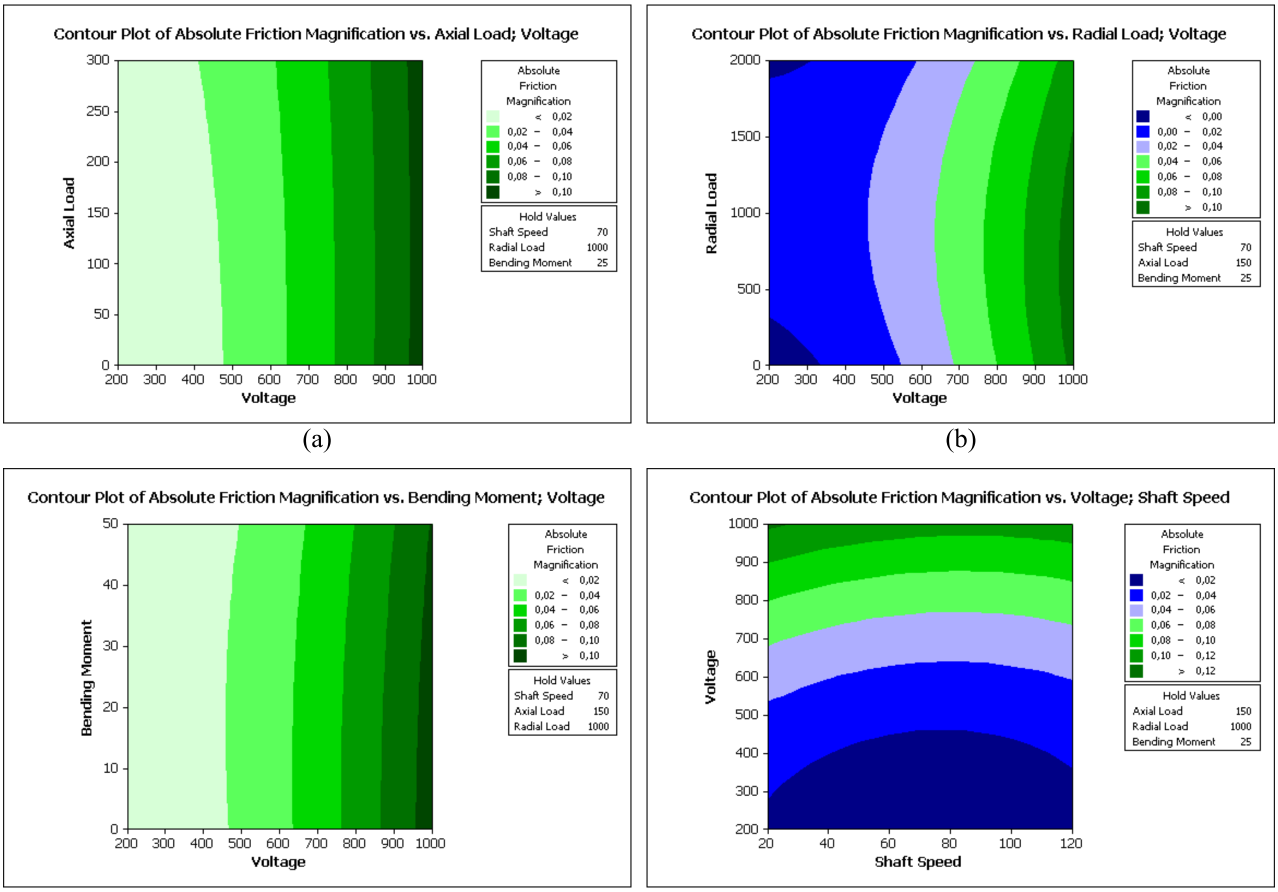


(a) (b)

(c)

Figure 3. Contour plots of the absolute friction magnification in the joint prototype with integrated plain bearings

Test results for the joint prototype with integrated rolling bearings show that the absolute friction magnification in the investigated range depends significant just on the applied voltage (Figure 4).



(a) (b)

(c) (d)

Figure 4. Contour plots of the absolute friction magnification in the joint prototype with integrated rolling bearings

Dependence of the friction magnification on voltage is directly proportional similar as in the joint with integrated plain bearings. Compared to the relative friction magnification which is presented in [14] there is no influence of the shaft speed. Friction in the bearings increases with higher velocities, but it is irrelevant because the friction difference (absolute friction magnification) caused by the actuators is constant (Figure 4(d)).

Knowing the influence of the parameters and according to the appropriate requirements (desired absolute and relative friction magnification) on the structure (joints) it is possible to develop tailor-made joints for different applications. For example, if high friction in joints is necessary because of better damping, it is better to use joints with plain bearings. This joint type is also recommended if joint locking is necessary because of avoiding singularities, configuration changing or calibrating. Otherwise, if friction in joints should be as low as possible, it is recommended to use the solution with rolling bearings. For eventual locking in that case it is necessary to have a separate adaptronic brake.

5. CONCLUSIONS

After closely analysing conventional concepts of the joints for parallel robots, it is apparent that they represent a compromise solution according to clearance and friction and it is not possible to adapt them to different operation conditions while the robot is in operation. New concepts, based on the integration of adaptronic components in the joints, offer a considerable advantage over the old concepts. They are characterized by the active adaptability whereby they are able to provide desired clearance and friction properties. Integration of the joints based on the presented concepts in real parallel robots should show how dynamic and damping performance as well as accuracy of parallel robots could be increased. This all would lead to shorter cycle times and therefore to a higher productivity.

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