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Introduction of the high performance area measure for the evaluation of metamorphic manipulator anatomies

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ABSTRACT

The modular metamorphic manipulator has been proposed in previous work as a concept of a robotic manipulator, where a single structure could be metamorphosed offline to different anatomies. In this paper, a global kinematic measure for the evaluation of the emerging anatomies, of a given structure of a class of 3 d.o.f. modular metamorphic manipulators is introduced. The proposed high performance area (HPA) measure depicts the dexterous workspace defined by a chosen threshold of a local kinematic index to meet the specifications of the given task. The region of the anatomy's workspace, where the selected local kinematic index meets the specifications is cross-sectioned by the XZ-plane in C-space, and the maximum area formed is the HPA. In order to reduce the computational burden, a procedure is proposed to approximate the HPA. The HPA is used to formulate an optimization problem for the determination of the optimal anatomy of a given metamorphic structure, which is solved using a genetic algorithm. A case study application of a 3 d.o.f. metamorphic structure is presented, using the manipulability measure and the conditioning index as local indices. The presented results are thoroughly discussed and the paper concludes with some hints for future work.

1. Introduction

As the implementation of the reconfiguration paradigm in the design of robot manipulators attracted robotic researchers during the last decades, some few different reconfigurable manipulators were proposed in the relative literature [1–3]. In general, the structure of the proposed reconfigurable manipulators was modular, where various types of interchangeable modules could be connected to structure a manipulator as per the end users' specific needs. Therefore, of the utmost importance is the development of methods for the determination of the optimal structure (anatomy) best fitting the end user (task) specifications.

The determination of the optimal anatomy for modular reconfigurable manipulators has been considered as a critical step in their design, since their main advantage is that; allowing the end user to match a specific anatomy to a specific task in order to achieve the highest possible manipulator performance. Although the anatomies constructed using the basic components share architectural characteristics with fixed anatomy robots, their optimal anatomy design problem is formulated in a different way than their fixed anatomy counterparts. Researchers mostly focus on the structural synthesis of parallel robots [2], while serial manipulator studies are very limited. A systematic approach for the structural synthesis of mechanically-constrained serial-type manipulators has been presented in Kou and Dai [18]. Given the design requirements — the manipulator's d.o.f. and the motion constraints of the end-effector — the possible joint connectivity assortment is developed, and then the kinematic types are assigned. Three general and eleven configuration and articulation rules can be used to constrain the end effector's motion based on the aforementioned requirements. In [4] the minimized degree of freedom approach was introduced as a method for the task based design of modular robot

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configurations. The Assembly Incidence Matrix (AIM) was proposed as a tool for representing modular configurations. The objective function was the weighted sum of the types of modules in the AIM, while task related local kinematic measures were used as design constraints. An approach using a configuration engine capable of generating different symmetric parallel and serial manipulator architectures for a given task was presented in [2] and [3]. The optimality criterion proposed was the energy consumption, under a number of constraints such as joint position, velocity and torque limits, singularity avoidance and collision avoidance.

In [5] another task based design of modular manipulators was presented, where the objective function was the root mean square of manipulability along the task. In [6] four performance measures were defined, the manipulability at working points, the error at working points, the required torque at working points and the joint movement from one working point to another. The objective function was the subtraction of the values of the latter three measures from the first one.

The presented methods for the determination of the optimal anatomy make use of either local kinematic measures or task based kinematic measures in order to take full advantage of the variety of anatomies a modular system can be structured to, and to select the one with the highest possible performance for the specific task. In the above presented works, genetic algorithms were used to search for the optimal anatomy of the modular robot.

Although reconfigurable robots greatly increase the flexibility of a robotic workcell, they present a drawback, since the manipulator has to be dismantled, at least partially, and reassembled to the new anatomy. The modular metamorphic serial manipulators were introduced as a class of open chain robots [7], whose structure can be easily metamorphosed to different anatomies without changing its topology, via the offline variation of the connecting modules. The design of the modular metamorphic manipulators can be a two stage process, due to the distinction between structure and anatomy, which for both fixed anatomy and modular reconfigurable robots is identical. Once the best structure is defined, the search for the optimal anatomy takes place. However, since the number of possible anatomies a single structure can be altered to is quite large, a global measure is required to characterize the performance behavior of the emerging anatomies of a structure in order to determine the optimal one for the given task specifications.

The dextrous workspace has been used for in manipulator optimal design and/or global workspace optimization. Methods and measures based on the determination of the dexterous workspace of a manipulator were presented in the relative literature for the dexterous workspace optimization of fixed anatomy manipulators.

A method for the optimization of the common workspace reachable by the four robotic arms of a medical robot was presented in [8]. The common workspace was defined as the common volume that was the union of the workspaces of all four arms of the robot. Two indices were defined, the area circumference ratio and the inverse condition number of the Jacobian for each arm which were aggregated to form the objective function. The optimization parameters were defined as the length of the first two links of an arm, the base orientation of the arms, the port spacing between the bases of the robot's arms and the minimum value of the inverse condition number required in the common workspace. An interval analysis based study for the design and comparison of 3 d.o.f. parallel kinematic machines was proposed in [9]. The authors proposed two design criteria, a regular workspace shape and a kinetostatic performance index. The dexterous workspace was defined as the portion of the manipulator's workspace where the selected kinetostatic measure (condition number) remains as homogeneous as possible.

A method for the determination of the optimal design parameters of a linear Delta robot so that its dexterous workspace would fit a prescribed cuboid workspace was presented in [10]. The method was based on the concept of performance charts, which depict the relationship between design parameters and performance criteria graphically and globally. In this work the reciprocal of the Jacobian's condition number was selected as a performance index for the derivation of the performance charts. In [11], a generic approach for the determination of the inverse reachability related to the kinematic chain of a robot was presented. This inversion was shown to assist the designer in the determination of suitable base poses to place the robot. The oriented reachability map was introduced and built by representing the inverse reachability data at the target pose. It graphically presented all possible robot base poses in the workspace of the robot along with their probability, for a given and fixed tool frame configuration.

A first conclusion from the above presented works is that the definition of dexterous workspace may vary depending on the type of robot and task to be performed. Although essentially it represents the region in a manipulator's workspace where certain performance requirements are met, the definition of the type of performance, the desired geometric characteristics of the dexterous workspace as well as the way in which the design specifications are considered leads to the different approaches. Regarding the modular metamorphic serial manipulators, the dexterous workspace proved to be a valuable tool for the designer in order to determine the best anatomy derived from a metamorphic structure according to the considered robot task.

In the present work, a global measure, termed high performance area (HPA), is proposed for the evaluation of 3 d.o.f. anatomies of a given metamorphic manipulator structure. The proposed measure belongs to the class of the dexterous workspace global measures, however it is defined for the evaluation of the modular metamorphic serial manipulators. Since the considered class of metamorphic manipulators utilizes only rotational joints, then the shape of their workspace is formulated by the rotation about the first joint in a given structure. Therefore the cross-section of the high performance part of the workspace with a plane on which the first joint axis lies provides a measure of this part of the workspace, called the HPA. Essentially it is an evaluation score for the selection of the best emerging anatomy of a metamorphic structure, however, it also provides the designer with practical information about the selected anatomy's high performance in a region of its workspace. As such the proposed measure can be implemented in either global or task based design approaches, depending on the designer requirements.

A description of the modular metamorphic manipulators and the case study of the metamorphic structure considered in this work are presented in Section 2, along with an investigation on the variation of the manipulability index and the condition number in the configuration space induced via the structure metamorphosis to different anatomies. The proposed global measure and the process for its value approximation are presented in Sections 3 and 4 respectively. An algorithm is proposed for the approximation of the presented HPA measure in order to limit the computational time required for its actual value calculation. The process for formulating