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Port-Based concepts in Robotics: from simple electric drives to complex fluid-solid dynamics interaction in flapping flight.

[1]Stefano Stramigioli

Port-based modelling is a methodology which treats physical systems modelling as the network interaction of physical components which can be described in an open way fashion, not needing any information about other parts they will be connected to to describe the total dynamics of a system. In order to use this powerful methodology in all possible situations, proper mathematical structures should be defined and this is expecially the case if the goal is to generalise this methodology to distributed parameters systems. In this introductory talk, the methodology will be presented with attention also for how via modelling, control can also be achieved for simple examples. Concluding, results in this field related to the www.portwings.eu project on robotic flapping flight will be presented.

Developing a Leader-Follower Kinematic-Based Control System for a Cable-Driven Hyper-Redundant Serial Manipulator

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Abstract. In this paper a cable-driven hyper-redundant manipulator using leader-follower control is explored. The proposed system is being developed for the purpose of exploration and inspection of highly confined spaces. Using a tele-operated joystick, an operator will have direct control over the end-effector, which will determine the trajectory and motion of the robotic system through the leader-follower control. To develop a control system for the manipulator, the relationships between the cables, motors and joints were first explored. Based on these relationships the system is modelled mathematically from the user to the end effector. Using the kinematic equations, a control system was devel- oped in MATLAB simulink. A prototype was developed to measure and validate kinematic relationships between the cables and joints of the sys- tem. Error detection and correction is implemented using proportional control, validating the Kp value using the prototype system. To verify the kinematics and proposed control system, a simulation was conducted using the MATLAB robotic toolbox. The simulation result demonstrated the promising capability of the proposed leader-follower control system in controlling the robot motion and trajectory.

Keywords: Hyper-redundant robots, kinematic analysis, semi-autonomous control, serial manipulators

Adapting Multi-Agent Swarm Robotics to Achieve Synchronised Behaviour from Production Line Automata

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Abstract. This paper describes a novel approach to swarm robotics that enables synchronised behav- iour from a number of automata that individually follow simple control rules, but whose interactions necessitate more complex behavioural patterns. A variation on Q-Learning is introduced, and it is shown that synchronised behaviour within set constraints can be learned. This paper reports on initial experimentation with these approaches, and on some of the promising results on behavioural syn- chronisation that have been obtained. The motivating application for this research was to enable greater concurrency from production line automata, where higher throughput or reduced footprint could be achieved if individual automata could be located closer together operating in tightly choreo- graphed synchrony. However, the research was designed in expectation that similar techniques might apply more widely to any circumstances featuring multiple interacting robotic systems but with prac- tical or commercial drivers against long periods of configuration or ramp-up time.

Keywords: Robotics, Machine Learning, Q-Learning, Synchronisation, Ramp-up time.

Using a Direct Multiple Shooting Method to Control a Quadrotor

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Abstract: A multiple direct fire method is considered to solve optimal control problems. The multiple direct multiple shooting method is a numerical method for solving limit value problems. The method divides the interval over which a solution is sought into several smaller intervals, solves an initial value problem in each of the smaller intervals, and imposes additional matching conditions to form a solution over the entire interval. This method transforms an optimal control problem into a non-linear programming problem. To solve the latter problem, the zeros of the Lagrange Jacobian are computed using Newton's method. Then, this method is illustrated by a numerical example and finally, applied to control a quadrotor in order to minimize energy.

Keywords: Optimal control, Multiple Shooting Method, Non-Linear Programming Problem, Newton's method, Quadrotor.

On the snappability and singularity-distance of frameworks with bars and triangular plates

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Abstract. In a recent article the author presented a method to measure the snapping capability – shortly called *snappability* – of bar-joint frameworks based on the total elastic strain energy by computing the deformation of all bars using Hooke's law and the definition of Cauchy/Engineering strain. Within the paper at hand, we extend this approach to isostatic frameworks composed of bars and triangular plates by using the physical concept of Green-Lagrange strain. An intrinsic pseudometric based on the resulting total elastic strain energy density cannot only be used for evaluating the snappability but also for measuring the distance to the closest singular configuration. The presented methods are demonstrated on the basis of the 3-legged planar parallel manipulator.

Keywords: Snapping framework, singularity distance, elastic deformation

Analysis of the Topology of the Singularity Set of Planar 3-RPR Parallel Robots with Linear Platforms

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Abstract. In [4] most of the results for a general 3-RPR planar robot with linear platforms are proven: there is a singularity-free path between two symmetrical direct kinematics solutions, there are no singularity-free paths between non-symmetrical direct kinematics solutions . We provide alternative and easy theoretical proofs of these results. We describe the topology of the kinematic singularities of these robots. We prove that the singularity-free set of the domain of the kinematic map for such robots consists of three components. One of our main results is the detail analysis of the special case i.e. when the anchor points of the moving platform and the fixed platform have the same cross-ratios. For this case we show: the connected components of the singularity-free set consists of 4 components, no direct kinematics solutions can be connected without crossing the singularity, the absolute value of the determinant of the Jacobian evaluates to the same number for any of the direct kinematics solutions. We provide some nice geometric properties of the direct kinematics solutions for this special case.

Keywords: direct kinematics, parallel planar robots, singularities

Using monodromy to statistically estimate the number of solutions

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Abstract. Synthesis problems for linkages in kinematics often yield large structured parameterized polynomial systems which generically have far fewer solutions than traditional upper bounds would suggest. This paper describes statistical models for estimating the generic number of solutions of such parameterized polynomial systems. The new approach extends previous work on success ratios of parameter homotopies to using monodromy loops as well as the addition of a trace test that provides a stopping criterion for validating that all solutions have been found. Several examples are presented demonstrating the method including Watt I six-bar motion generation problems.

Keywords: statistical estimation, motion generation problems, monodromy, trace test, numerical algebraic geometry

On Orientation, Position, and Attitude Singularities of General 3R Chains

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Abstract. The characterization of the workspace for general spatial 3R chains with skew joint axes is refined by describing the variety of singular displacements as the union of the singular configuration manifolds of orientation type, position type, and attitude type. The surface of attitude singularities is revealed by transferring the singularity sets of spherical 3R chains with intersecting joint axes to the geometry of spatial kinematic chains with skew, non-intersecting joint axes. For this purpose, the degeneracy of a screw system is analyzed by means of a particular angle concept for a set of three oriented lines in space. The obtained argumentation is expressed in terms of geometric manipulator Jacobians completing previous results.

Keywords: Computational kinematics, workspace analysis, singularity analysis, line geometry, principle of transference, adjoint representation.

Mathematics of Robotic Manipulators: Theory and Applications

Abstract

There is an organic paradigm between Mathematics and Robotic Engineering. Mathematical modelling helps engineers to develop analytical and numerical solutions for robotic manipulators. Indeed, these mathematical formulations are the building blocks that capture the kinematics and dynamics of these highly nonlinear man-made machines. Accurate models play a decisive role in designing precise motion planning and control algorithms; this is essential for manoeuvring along the desired trajectory whilst avoiding obstacles and singularities. Theoretically, both terrestrial and space-based robotic manipulators use the same fundamental modelling technique but practically, there are many differences due to their contrasting operating environments. In this talk, Prof Saaj will talk about the art of mathematical modelling applied to robotic manipulators and its interface with the trajectory planner, controller and actuator. The choice between using a linearised model and a non-linear model will be discussed based on models and control solutions developed for Space robots.

Speaker Biography

Prof Mini C. Saaj is the Global Chair in Robotic Engineering at the University of Lincoln, UK, where she is also the lead for research in Industrial Digitalisation and System Intelligence. Previously, she was the Head of Robotics and Control research group and the Director of Post Graduate Research at the Surrey Space Centre, UK. Her expertise is in modeling and control of spacecraft, design and control of rigid and flexible manipulators, systems engineering using Model-Based Systems Engineering approach, design and control of wheeled and legged planetary rovers, bio-robotics and flexible medical robotics. Prof. Saaj has secured research grants over £3.8M as lead and co-investigator. In addition to publishing 98 articles, she has successfully supervised several post-doctoral Research Fellows and PhD students. Being a leading female Space engineer and Roboticist, Prof. Saaj actively promotes Space Engineering education. She was a Flying Lecturer with the EngineeringUK for the 'Engineers make it happen' campaign (2008-2010). She won the Airbus - Royal Academy of Engineering Secondment award (2009) and the University of Surrey Vice Chancellor's Teaching Excellence award in 2013. Prof. Saaj is a Chartered Engineer with the Engineering Council, UK and a Senior Member of IEEE and AIAA and a member of IEEE Women in Engineering. More details can be found at:

https://staff.lincoln.ac.uk/f3bf7246-9b69-4e6c-9157-f8c4d7221fc3

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Optimization-based kinematic synthesis using homotopy continuation

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Kinematic synthesis aims to find the dimensions of a mechanism after desired constraints have been posed on its motion. For exact synthesis, the number of constraints and dimensional design variables are equal. For approximate synthesis, the former exceeds the latter. In this work, approximate synthesis is tackled by an optimization formulation that is invariant to the number of constraint specifications. The objective function, which is polynomial in nature, is a sum of squares of the error in the kinematic constraint equations at the task specifications. Using the first-order necessary conditions of optimality, solving the optimization problem boils down to that of finding the roots of a system of polynomial equations. Although these systems are of a larger total degree than their respective exact synthesis systems, homotopy continuation techniques based on multi-homogeneous structure and monodromy-based methods can be used to solve these systems. In the ab initio step, the system of equations is solved for a generic set of complex number specifications. Subsequent physical problems are solved via parameter homotopy using the start system computed in the ab initio step. The roots of such systems comprise all the stationary points including minima, saddles, and maxima. Since secondary considerations further dictate whether a minimum is feasible for a practical design, some low index saddles are also found to lead to suitable designs. Investigation into the Morse- Smale complexes starting from these low index saddles into the adjoining minima leads to useful families of solutions. This provides the designer with parameterized sets of design candidates that are not possible without the computation of all possible critical points to the optimization problem.

Combinatorics of a Discrete Trajectory Space for Robot Motion Planning

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Abstract. Motion planning is a difficult problem in robot control. The complexity of the problem is directly related to the dimension of the robot's configuration space. While in many theoretical calculations and practical applications the configuration space is modeled as a continuous space, we present a discrete robot model based on the fundamental hardware specifications of a robot. Using lattice path methods, we provide estimates for the complexity of motion planning by counting the number of possible trajectories in a discrete robot configuration space.

Keywords: Discrete robot model, Configuration space complexity, Lattice paths

Active Matter as a Path Planning Interpreter

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Abstract. This paper describes a novel approach to controlling Active Matter by interpreting it as a form of automata. Active Matter systems exhibit many different forms of complex behaviour, some of these systems exhibit memory, with previous stimulations affecting the reaction from future stimulations. Much work has been done to find alternative computational mediums in organic and chemical systems, additionally much work has been done in the field of soft robotics exploring compliant materials and actuators. Active Matter can serve both these fields and bridge between them, allowing a single material to house both the actuator and control. With these elements so close this allows for extremely compact robotic systems, where a minuet actuator can function semi- independently. Active Matter can be used to extend the computational ability of the system as they can be used as a computational resource since their behaviour can be compared to that of an automaton, transitioning from state to state with input signals. Using EAP gels as an example of Active Matter that exhibit the necessary behaviour, a framework is introduced that adapts the behaviour to a Moore machine by converting the movement and hysteresis of the matter to a series of states, using a simplified model. The directed graph is generated, and probability distribution of the states demonstrated. This shows the optimization ability of the matter where that the matter always displays an optimized form of the generalized directed graph. By creating a framework for these systems their motion can be used to their fullest potential, utilizing them as a path planning interpreter translating a sequence of inputs to a sequence of movements. This allows a portion of the control system to be offloaded onto the Active Matter itself allowing for the creation of compact integrated robotic systems.

Keywords: Active Matter, Automaton, Path Planning

Linear registration and robot motion planning

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Abstract. This paper presents preliminary results of applying the image registration paradigm to robotics. Specifically, we explore a specific version of the image registration problem, called linear, whose registering diffeomorphism is defined by the flow of a linear, time-dependent dynamical system. Optimality conditions for the linear registration have been provided, and the registering diffeomorphism derived explicitly. Results are applied to motion planning of manipulation and mobile robots. Computer simulations serve as a means for evaluation of the results. An extension to multiple point robot motion planning is proposed.

Keywords: registration problem, deformation, linear dynamical system, vector field, diffeomorphism, robot motion planning

Real-time planning for cooperative maze exploration

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As robotics evolves, more and more work is being done to have the robot replace man in dangerous working conditions.

Examples of such dangerous working conditions are searching for victims in burning buildings, passing through a minefield or patrolling the streets with an increased crime rate. All of the above problems can be viewed as a problem in which one or more agents are exploring an unknown maze.

Many single-agent maze exploration algorithms have been implemented, but extending them to multi-agent systems is not always simple and feasible.

We propose a solution for the problem where a cooperative multi-agent system of automated vehicles is used to explore an unknown maze with stationary targets. The algorithm uses a potential field to explore the maze with a built- in cooperative behavior of agents which includes collision avoidance, coverage coordination, and optimal path planning.Proposed algorithm was created on the basis of HEDAC (Heat Equation Driven Area Coverage) introduced by Ivi´c, Crnkovi´c and Mezi´c in [1], and which has already been successfully applied for motion control for autonomous heterogeneous multi-agent area search in uncertain conditions [2], and for motion control for multi-agent non-uniform spraying [3]

We made a comparison with the algorithm of similar objective and application. The proposed algorithm results show obvious improvement and we can demonstrate that the new algorithm can be applied to all maze types and not only to special cases.

In performed tests, the proposed algorithm proved to be robust, adaptive, scalable, and computationally inexpensive which enables real-time planning.

Keywords: cooperation, multi-agent system, maze, exploration

References

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Flexible placements of graphs with rotational symmetry

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Abstract. We study the existence of an n-fold rotationally symmetric placement of a symmetric graph in the plane allowing a continuous deformation that preserves the symmetry and the distances between adjacent vertices. We show that such a flexible placement exists if and only if the graph has a NAC-colouring satisfying an additional property on the symmetry; a NAC-colouring is a surjective edge colouring by two colours such that every cycle is either monochromatic, or there are at least two edges of each colour.

C-space Analysis using Tropical Geometry

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Abstract. Configuration space (C-space) of a mechanism is a real variety describing the set of feasible configurations that it can attain. To understand the behavior of a mechanism, it is crucial to identify and scrutinize especially the singular points of its C-space. They usually appear when the variety intersects itself, leading to different branches of motion. There exist many approaches to detect those intersections if they are transversal. However, the problem remains challenging if there are tangential, cuspidal, inter-dimensional or a combination of these intersections. This paper exploits an approach acquired from tropical geometry to analyze the neighborhood of any point on C-spaces of 1-*dof* mechanisms. This is done by finding the approximate rational parametrization of the curve(s) passing through the given point using Puiseux series. The proposed approach is shown to succesfully detect the transversal branchings in two foldable four bar mechanisms and a cusp in the configuration curve of the double Watt mechanism.

Keywords: kinematics, configuration space, singularity analysis, tropical geometry, Puiseux series

A Remarkable 8R-Mechanism

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Abstract. We present some observations on a closed 8R-mechanism with the remarkable property that locking one of its joints in any configuration (of a suitable two-dimensional component of the configuration space) restricts the mechanism to a one-dimensional motion where automatically every other joint is locked as well. Equivalently, at any configuration, the four joints of even index and the four joints of odd index form respective Bennett mechanisms. The mechanism is constructed from a bivariate quaternion polynomial of bidegree $(2, 2)$ which allows two factorisations with linear univariate factors. So far, only isolated examples are known.

Keywords: Quaternions · dual quaternions · bivariate polynomial · factorisation · Bennett mechanism

Calculating the Segmented Helix Formed by Repetitions of Identical Subunits

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Abstract. Eric Lord has observed:

> In nature, helical structures arise when identical structural subunits combine sequentially, the orientational and translational relation between each unit and its predecessor remaining constant.[1]

A complete version of this paper proves this[3]. If a robot is composed of modular structural subunits that can change their shape or relation, the shape of the robot can change. If they all change in the same way, the robot will be a segmented helix of varying length and curvature. Closed-form expressions are given for the parameters of the segmented helix generated from the intrinsic properties of a chained object and its conjoining rule. The construction of these from the intrinsic properties of the rule for conjoining repeated subunits of arbitrary shape is provided, allowing the complete parameters describing the unique segmented helix generated by arbitrary stackings to be easily calculated. Free-libre open-source interactive software and a website is provided which performs this computation for arbitrary prisms along with interactive 3D visualization[2]. This allows the deduction of intrinsic properties of a repeated subunit from known properties of a segmented helix, as a chemist might want to do. Because the algorithms are efficient, a repeated subunit can be designed to create a segmented helix of desired properties, as a mechanical engineer or roboticist might want. A theorem, proved in a longer version[3], is stated that any chain can be transformed continuously between a toroid-like helix and a maximally-extended helix by varying joint-face normal twist.

Keywords: Helix, Variable Geometry Truss, Segmented Helix, Solid Geometry, Screw Theory, Platonic Helix
Mathematics Subject Classiftcation: 97G40, 52B12

On the Geometry of some Localisation Problems in Robotics

J.M. Selig

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Abstract

In this work a couple of localisation problems for mobile robots are revisited. Specifically the problem of finding the location of the robot from the distances to fixed beacons and using time differences of arrivals of signals at several stations are addressed. The aim is to study the geometry of these problems. In particular, tetracyclic coordinates are used to represent circles in the plane. These coordinates are an old idea that have not been used for these types of problem before. The coordinates help to simplify expressions and hence expose the underlying geometric ideas involved in these problems.

Keywords: Localisation, Tetracyclic coordinates, Cyclographic coordinates, Osculating circles.

Big robotics

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With the exception of their fascinating and elegant mathematics, robots are unremarkable things that do whatever they are programmed to do. Their increasingly ubiquitous use in manufacturing over the last forty + years has proved they are highly dextrous and very reliable automatons and have doubtless had a very positive impact on the economy of any country that uses them. But from the layperson's perspective it may be somewhat curious that, despite their widespread use and acceptance, research into robotic systems has only relatively recently become one of the government's top priorities.

This new science lies partly in the increasing levels of sophistication necessary to imbue pseudo-anthropomorphic perception, decision making and reasoning into robotic systems and the real-time autonomous control of increasingly agile mobile robotic systems. Robot kinematics and solutions of inverse kinematic problems has given way to taking account of dynamics and optimising inverse dynamics. Configuration space of kinematic problems has given way to state-space in the case of Lagrangian models or the phase-space coordinates of Hamiltonian systems.

These more recent developments, which may have found their roots in the 1970s are becoming in quite widespread use now. So much so, that the field is starting to rub shoulders with control theories and theories of structural dynamics.

At the same time, artificial intelligence has provided us with deeper and deeper learning algorithms and even though their strongest areas are in visual processing and obkect recognition, they are also nowadays being combined with physics-based solvers.

The evolution of robotic systems has come a long way since their invention in the mid-1950s, but one could argue that present day robotics just do the work a person could do (with the right PPE), only faster, for longer and with greater precision. The technology and mathematics needed to create a legged robot such as a robotic dog is not widely appreciated by the general public (and why should it be?) whilst its crowd-pleasing dog-like behaviour certainly is.

The Systems (robots, robot models), Interactions (with environments, constraints etc.) and Goals (tasks, performance measures) realised in computer code running in real-time is difficult enough when just considering robot kinematics. However, some of the problems that still remain are those involving “big” robots, such as automating container crane operations or underwater craneage, where payload dynamics, actuator dynamics and the interaction between the two dominate. Some use-cases of “big” robotics include the design and control of long, slender arms needed for manipulating heavy inertial objects in space, or in other areas where robot dynamics cannot be ignored.

The DEMO EUROfusion project envisions a fusion reactor of such dimensions that the internal absorption layers (blankets) within the tokamak could have a mass exceeding 80 tonnes. These slender and flexible objects have to be lifted out of the tokamak during maintenance with millimetric precision. Although the design is not finalised, it is likely that these objects will require rotation about the horizontal access in order to navigate the path from inside the tokamak. The robotic systems required to do this are unlikely to be rigid enough to the control system designers to ignore their dynamics, the dynamics of the load itself and the exchange of energy between the two. The proof of commercial viability will depend to some extent on the timeliness of such maintenance tasks.

Robots will need with the ability to lift unknown objects, assess the mass distribution and any flexibility or instability and decide on a lifting strategy. They will need to be sufficiently robust that they can operate with equal efficiency on unknown terrain (however, this is hardly new).

As space exploration gives way to space industrialisation, larger and larger objects will need to be constructed and the commercial reality means that time pressures, as well as safety, precision and other aspects will all feature in the optimisation models used for control.

So the challenge of “big” robots (besides thinking of a better name) is the combination of all these attributes. Humans can see, hear and feel. “Big” robots will use a range of other sensor modalities, combine them and calculate properties such as sheer stress and dynamics in real-time. These sensory and control capabilities will far exceed those of humans.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Zero-sum cycles in flexible non-triangular polyhedra

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Abstract. Finding necessary conditions for the geometry of flexible polyhedra is a classical problem that has received attention also in recent times. For flexible polyhedra with triangular faces, we showed in a previous work the existence of cycles with a sign assignment for their edges, such that the signed sum of the edge lengths along the cycle is zero. In this work, we extend this result to flexible non-triangular polyhedra.

Synthesis of Planar Stiffness

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Abstract

In this work the problem of designing systems of springs to achieve a desired stiffness matrix is considered. Only planar configurations are studied. After a brief section outlining the theory of the stiffness of planar systems the planar stiffness matrix of three typical design elements are found, simple springs, beams and pairs of stretched springs. A final section shows how arbitrary stiffness matrices can be achieved using three simple springs or two stretched spring pairs.

Keywords: Stiffness matrix, springs, beams.

Optimization of Cartesian Tasks with Configuration Selection

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Abstract. A basic task in the design of an industrial robot application is the relative placement of robot and workpiece. Process points are defined in Cartesian coordinates relative to the workpiece coordinate system, and the workpiece has to be located such that the robot can reach all points. Finding such a location is still an iterative procedure based on the developers' intuition. One difficulty is the choice of one of the several solutions of the backward transform of a typical 6R robot. We present a novel algorithm that simultaneously optimizes the workpiece location and the robot configuration at all process points using higher order optimization algorithms. A key ingredient is the extension of the robot with a virtual prismatic axis. The practical feasibility of the approach is shown with an example using a commercial industrial robot.

Keywords: configuration, virtual axis, differentiable optimization