Operating Unknown Constrained Mechanisms with Compliant Robots

Ewald Lutscher and Gordon Cheng
Institute for Cognitive Systems, Technische Universität München, Germany - (www.ics.ei.tum.de)

Abstract

We present an approach for operating unknown one-degree-of-freedom (DoF) mechanisms, using a compliant robot. The key aspect of our approach is that we make only little assumptions about the operated mechanism in terms of imposed kinematic constraints on the end-effector as well as dynamic properties, which can not always be neglected.
The proposed system consists of: i) a constraint estimator using end-effector velocity measurements to obtain the first order constraint parameter; ii) a controller, using the estimation to produce adequate set-points for the compliant robot; and iii) a controller for a moving base to extend the workspace of the attached manipulator.
The proposed scheme was implemented on two conceptually different robots which demonstrates the general applicability on different hardware. The implementations were successfully tested on various mechanisms in human environment, like doors, drawers or cranks.

1 Introduction

A new need for compliant robots is becoming apparent, with robots leaving their predefined workplaces and entering human environments. First and utmost reason being new safety concerns of these systems, as robots are expected to physically interact with humans, as the environment becomes more uncertain, programmers can no longer rely on given models or maps without the risk of damaging the robot or its surroundings. Especially, when the robot is in contact with the environment even small errors in the positioning can have devastating results. Even simple tasks, like opening a cupboard, are not straight forward and require a new robot design and control paradigm.
With this work we present a general paradigm for operating unknown constrained mechanisms, like doors and drawers of different kinds.
A compliant robot, where the compliance is realized in terms of a physical relationship between forces and motions, what is for example realized in impedance control [5]. The interaction-force of the robot is controlled indirectly via the relationship between a virtual or desired set-point and the physical robot. For joint compliance the applied force vector is not necessarily aligned with the position displacement. This case is treated more closely in [8]. The application programmers challenge is to design a set-point-controller, which makes the robot interact with its environment in a desired way.
We are developing a set-point-controller which uses the helpful given fact, that most mechanisms in human environment have only one DoF. Supposed sufficiently tight coupling between end-effector and operated mechanism, the end-effector trajectory is determined by the mechanism itself. This important property of such constrained mechanisms is exploited to estimate the direction of possible movements by observing the current translational velocity of the end-effector.
The main advantage of our approach is, that we do not assume detailed knowledge neither about the constraints, nor the required interaction forces. Especially the unknown forces make it hard to apply force tracking schemes. So, instead of tracking desired forces directly, we explore the manipulators workspace with its virtual configuration, while continuously estimating the possible direction of motion.
To enable a large class of robots using only joint encoder measurements, we avoid additional sensors (e.g. tactile) or specialized end-effectors. The present work is focused on the concrete implementation of our approach on two different systems and its practical applicability. The two systems are: 1) an admittance controlled mobile manipulator; and 2) a stationary manipulator running joint-space impedance control. For the mobile case, an approach to resolve base movement is also presented in Section 2.3.

1.1 Related Work

Practical implementations for constrained manipulation often regard it as a planning problem, e.g. [10]. These approaches require in general specific knowledge about the constraints and are prone to modelling errors and uncertainties. A general framework for manipulation under physical constraints is presented in [7], merging a Kalman-Filter based constraint estimator and a force controller to fulfil different positioning tasks. However, a purely velocity and force controllable subspaces is assumed there, which cannot be guaranteed when operating in human environment, e.g. spring loaded doors. De Luca captures kinematic and dynamic constraints in his theoretical framework [2], however, it still lack a real-world implementation. Recent work of Jain *et al.* address the particular task of pulling open doors and drawers with a prosthetic hook, by setting an appropriate set-point for the impedance controlled manipulator [6]. They referred to this approach as equilibrium point control. In [11] an additionally learned kinematic model of the mechanism is used in conjunction with the algorithm developed in [6] to improve its performance. Their focus was on robust task execution, so spe-

cific assumptions regarding the type of the constraint and required forces were made.
In [9], we proposed a set-point controller for an admittance-controlled mobile manipulator combined with a constraint estimator based on filtering of the end-effector velocity. In [8], we formulated a general paradigm and extended the framework to robots with compliant joints. In the present work, we want to present a general velocity based implementation of the proposed method for Cartesian and joint-compliant robots.

1.2 Manipulator Control

Manipulator Representation

The end-effector velocity $\boldsymbol{v}$, of a manipulator is related to the joint velocities $\dot{\boldsymbol{q}}$ with

$$\boldsymbol{v} = \begin{pmatrix} \dot{\boldsymbol{p}} \\ \boldsymbol{\omega} \end{pmatrix} = \boldsymbol{J}(\boldsymbol{q})\dot{\boldsymbol{q}},$$

where $\boldsymbol{v}$ is composed of the translational $\dot{\boldsymbol{p}}$ and the angular velocity $\boldsymbol{\omega}$ of the end-effector. In the following the dependence on $\boldsymbol{q}$ will be omitted for the sake of brevity. The base Jacobian $\boldsymbol{J}$ can be used to compute an instantaneous inverse kinematics with

$$\dot{\boldsymbol{q}} = \boldsymbol{J}^{-1}\boldsymbol{v}, \tag{1}$$

assuming $\boldsymbol{J}$ has full rank. In case of $n > 6$, the inverse $\boldsymbol{J}^{-1}$ can be replaced by the generalized Moore-Penrose pseudoinverse $\boldsymbol{J}^{\#}$, resolving redundancy by minimizing the norm $||\dot{\boldsymbol{q}}||$.
Another useful property of $\boldsymbol{J}$, is that its transpose relates the applied end-effector forces $\boldsymbol{f}$ and moments $\boldsymbol{m}$ to joint torques

$$\boldsymbol{\tau} = \boldsymbol{J}^T\boldsymbol{h} \tag{2}$$

where $\boldsymbol{h}$ is the end-effector wrench denoted as $\boldsymbol{h} = [\boldsymbol{f},\ \boldsymbol{m}]^T$.

Indirect Force Control

Indirect force control schemes establish a static relationship between the deviation of the manipulators actual configuration from the desired one and the applied force or torques utilizing a virtual stiffness matrix. This relationship can be either established at the end-effector or at joint-level, where joint-level compliance is in general easier to realize since it does not necessarily require force/torque sensors.
Control interfaces of this type are for example (Cartesian) impedance control [5], regulating the physical behaviour of the end-effector to that of a desired target impedance with virtual inertia $\boldsymbol{M}_p$, damping $\boldsymbol{D}_p$ and stiffness $\boldsymbol{K}_p$, being all positive definite 3×3 matrices when regarding only translational motion. The interaction force is then

$$\boldsymbol{f} = \boldsymbol{M}_p\Delta\ddot{\boldsymbol{p}} + \boldsymbol{D}_p\Delta\dot{\boldsymbol{p}} + \boldsymbol{K}_p\Delta\boldsymbol{p}, \tag{3}$$

The position deviation in impedance control is the difference between desired and actual position of the end-effector, $\Delta\boldsymbol{p} = \boldsymbol{p}_d - \boldsymbol{p}$ which is aligned with the static interaction force, assumed $\boldsymbol{K}_p$ has only equal diagonal entries. As $\ddot{\boldsymbol{q}}_d$ and $\dot{\boldsymbol{q}}_d$ are usually zero, (3) can be rewritten as

$$\boldsymbol{f} = -\boldsymbol{M}_p\ddot{\boldsymbol{p}} - \boldsymbol{D}_p\dot{\boldsymbol{p}} + \boldsymbol{K}_p\Delta\boldsymbol{p},$$

The impedance control architecture can also be realized in joint space, realizing

$$\boldsymbol{\tau} = -\boldsymbol{M}_q\ddot{\boldsymbol{q}} - \boldsymbol{D}_q\dot{\boldsymbol{q}} + \boldsymbol{K}_q\Delta\boldsymbol{q},$$

with $\boldsymbol{M}_q$, $\boldsymbol{D}_q$ and $\boldsymbol{K}_q$ being positive definite $n \times n$ mass, damping and stiffness matrices in joint space.
This is, despite neglected dynamic forces, conceptually similar to a joint-space PD-controller with compensation of the gravitational torques $\boldsymbol{g}(\boldsymbol{q})$:

$$\boldsymbol{\tau} = \boldsymbol{K}_q\Delta\boldsymbol{q} - \boldsymbol{D}_q\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q})$$

For all variants of indirect force control an interaction force is indirectly introduced into the system via the desired Cartesian or joint-space set-point.
These schemes have proven excellent stability properties facing unknown interaction forces [12, 5], hence making them a popular scheme when operating in unknown environments.

2 A Manipulation Architecture for Constrained Mechanisms

For most practical cases it is sufficient to focus on translational motions, assuming locally unconstrained orientation. This is due to the fact that a perfect power grasp is hard to achieve in an unknown environment and little rotations are basically always possible, due to slippage or purposely relaxed task constraints, e.g. with caging grasps [3].

2.1 Constraint Estimator

We are applying a filter to obtain an estimate of $\boldsymbol{d}_p$, which is the tangent of the one-dimensional constraint manifold or the first order constraint parameter. As proposed in [9] we are filtering the translational Cartesian velocity signal $\dot{\boldsymbol{p}}$. For this we are using a simple moving average filter, which is the unweighted mean of the previous N measurements, where N is the window-width of the filter. For a discrete filter, one can write

$$\hat{\boldsymbol{d}}_p = \text{norm}(\frac{1}{N}\sum_{k=0}^{N}\dot{\boldsymbol{p}}_{i-k})$$

where $\dot{\boldsymbol{p}}_{i-k}$ is the measured translational end-effector velocity at time-step i. The function norm($\bullet$) is a normalization operator. As the normalization is applied after filtering, faster velocities have a bigger impact on the outcome than slower ones.

In addition, we apply dead-banding to exclude small, hence noisy measurements from the estimation. If the absolute value of the measured $\dot{\boldsymbol{p}}$ is below the dead-band threshold, it is dropped and some constant vector is assigned to $\dot{\boldsymbol{p}}$, e.g. some end-effector axis or the last valid estimation.
This local estimator allows us to track different trajectories without previous knowledge or laborious learning.

2.2 Set-Point-Controller

In contrast to usual force tracking, we have no knowledge of the required interaction force. Therefore, we explore the workspace continuously with the virtual configuration $\boldsymbol{q}_d$, respectively the virtual end-effector position $\boldsymbol{p}_d$ for Cartesian compliance, in order to generate a force along the estimated direction $\hat{\boldsymbol{d}}_p$[1].
Our set-point-controller provides a velocity input $\boldsymbol{u}$ for the virtual manipulator, which has the general form

$$\boldsymbol{u} = \boldsymbol{u}_{\text{exp}} + \boldsymbol{u}_{\text{cor}},$$

where $\boldsymbol{u}_{\text{exp}}$ is an exploration term and $\boldsymbol{u}_{\text{cor}}$ is a correction, adapting $\boldsymbol{q}_{\boldsymbol{d}}$ to changing conditions, like changing manipulator configuration or new constraint estimations.

Cartesian Compliance

For Cartesian compliance, exploring along $\hat{\boldsymbol{d}}_p$ has the desired effect of building up a potential along $\hat{\boldsymbol{d}}_p$. Using (1) one obtains

$$\boldsymbol{u}_{\text{exp}} = \boldsymbol{J}^{\#}[\nu_d \hat{\boldsymbol{d}}_p,\ \boldsymbol{0}]^T \qquad (4)$$

with ν_d as desired end-effector translational velocity magnitude, determining the desired exploration velocity. As the stiffness matrix $\boldsymbol{K}_p$ has usually the same entries for every direction, it has no effect on the direction of the applied force and hence can be omitted.
The correction term in this case has to maintain $\boldsymbol{\Delta p} \parallel \hat{\boldsymbol{d}}_{\boldsymbol{p}}$, keeping the position deviation, hence the static forces, aligned with $\hat{\boldsymbol{d}}_{\boldsymbol{p}}$. To realize this, one can for example add a term like

$$\boldsymbol{u}_{\text{cor}} = -k_{\text{cor}} \boldsymbol{J}^{\#}[\boldsymbol{\Delta} \hat{\boldsymbol{p}}_{\perp} \boldsymbol{0}]^T \qquad (5)$$

where $\boldsymbol{\Delta}\hat{\boldsymbol{p}}_{\perp}$ is obtained from the orthogonal decomposition of $\boldsymbol{\Delta p}$ with respect to $\hat{\boldsymbol{d}}_p$ via

$$\boldsymbol{\Delta}\hat{\boldsymbol{p}}_{\perp} = (\boldsymbol{I}_3 - \hat{\boldsymbol{d}}_p \hat{\boldsymbol{d}}_p^T)\boldsymbol{\Delta p}.$$

$\boldsymbol{I}_3$ denotes the 3×3 identity matrix.

Joint Compliance

Considering (2), for joint level compliance an exploration term like

$$\boldsymbol{u}_{\text{exp}} = \boldsymbol{K}_q^{-1} \boldsymbol{J}^T [\kappa_d \hat{\boldsymbol{d}}_p,\ \boldsymbol{0}]^T \qquad (6)$$

where κ_d is a constant positive value equivalent to ν_d in (4), will build up a static force along $\hat{\boldsymbol{d}}_p$. Note that κ_d denotes the rate of the force build-up.
Computing a correction term for this case requires the joint-space equivalent of $\hat{\boldsymbol{d}}_p$, which can be obtained from

$$\hat{\boldsymbol{d}}_q = \frac{\boldsymbol{u}_{\text{exp}}}{\|\boldsymbol{u}_{\text{exp}}\|}.$$

The joint position deviation $\boldsymbol{\Delta q}$ can now also be orthogonally decomposed with respect to $\hat{\boldsymbol{d}}_q$, giving the orthogonal component

$$\boldsymbol{\Delta}\hat{\boldsymbol{q}}_{\perp} = (\boldsymbol{I}_n - \hat{\boldsymbol{d}}_q \hat{\boldsymbol{d}}_q^T)\boldsymbol{\Delta q}.$$

where $\boldsymbol{I}_n$ denotes the $n \times n$ identity matrix.
Finally we can state the correction term in joint space

$$\boldsymbol{u}_{\text{cor}} = -k_{\text{cor}} \boldsymbol{\Delta}\hat{\boldsymbol{q}}_{\perp} \qquad (7)$$

similar to (5), compensating for the erroneous component $\boldsymbol{\Delta}\hat{\boldsymbol{q}}_{\perp}$.

2.3 Incorporating a Moving Base

A stationary manipulator has a highly limited workspace. Even a common task, like opening a cupboard door can be unaccomplishable for such a constricted robot. More flexibility by extension of the workspace can be achieved by mounting the manipulator on a mobile platform. For now, external obstacles are neglected and base motion is implemented in terms of a master-slave relationship to the manipulator, where the platform movement $\boldsymbol{v}_{\text{base}}$ is compensated by the arm with the modified command

$$\tilde{\boldsymbol{v}}_{\text{arm}} = \boldsymbol{v}_{\text{arm}} - \boldsymbol{v}_{\text{base}}, \qquad (8)$$

so that base movement does not affect the global end-effector position. Note that $\tilde{\boldsymbol{v}}_{\text{arm}}$, $\boldsymbol{v}_{\text{arm}}$ and $\boldsymbol{v}_{\text{base}}$ are expressed in the two dimensional frame, spanning a plane parallel to the floor. This base-control strategy complements seamlessly the existing manipulator controller.
A simple platform controller has two tasks with different priorities. The first task assures that the arm does not collide with the platform. The second task considers an arbitrary quality function to avoid unwanted configurations of the arm, which are in general close to singularities or joint limits.

Collision Avoidance

The collision avoidance problem is solved by defining artificial repelling potential or velocity fields between arm and base. The goal is to prevent intrusion of the arm into a critical zone around the platform. The critical zone has to be defined in a way that all collision possibilities are covered.

[1] A hat indicates estimated values or values which depend on estimations

Keeping Manipulator inside Workspace

The mobile base has also to execute movements preventing the manipulator to reach the limits of its workspace, extending it to the complete plane parallel to the floor. A way to solve that problem is to first define a quality function $F(\boldsymbol{q})$, which gives the distance to the manipulators workspace. In terms of joint limits a function can be defined as

$$F(\boldsymbol{q}) = -\frac{1}{2n}\sum_{i=1}^{n}\left(\frac{q_i - \bar{q}_i}{q_{iM} - q_{im}}\right)^2, \tag{9}$$

where n is the number of joints, q_i a particular joint angle, q_{im} the according lower joint limit, q_{iM} the according upper joint limit and $\bar{q}_i = \frac{q_{iM}+q_{im}}{2}$. In most practical cases the joints where a singularity can occur are known and one can avoid such configurations, by setting conservative limits to prevent singularities (e.g. elbow singularity).

With (8) the base is only able to affect the manipulators position in the floor-parallel plane, hence (9) should only be evaluated in this plane. Since this would require solving a global inverse kinematics problem, only a local evaluation at $F(\boldsymbol{q} + \boldsymbol{\delta q})$ of the quality function is possible, where $\boldsymbol{\delta q}$ can be computed from a sufficently small $\boldsymbol{\delta p}$ be means of instantaneous inverse kinematics (1), effectively giving us the gradient of F at $\boldsymbol{q}$.

We can now apply standard numerical optimization algorithms to find the optimal end-effector configuration with respect to possible base translations. **Figure 1** shows the contour-plot of F for an exemplary configuration of the Accrea manipulator [1].

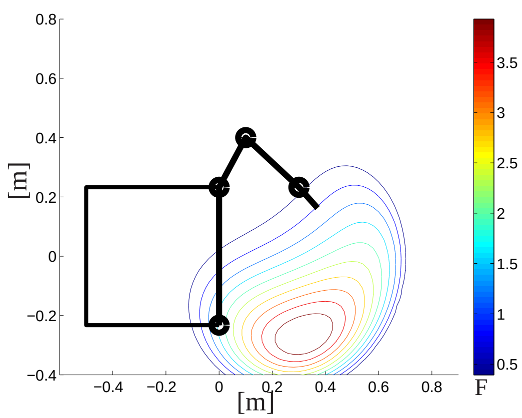

Figure 1: Quality function depending on the end-effector position in the floor-parallel-plane

Two kinds of behaviors can be realized: 1) the platform could either be commanded to stay always in a small area around the optimal configuration of the end-effector; or 2) start to approach this optimal point when the joint limits are getting close.

The entire velocity command is the superposition of collision avoidance and optimization term.

3 Case Studies

The proposed general approach was implemented on two different robots: 1) the Accrea Manipulator mounted on an omnidirectional base [1]; and 2) a stationary KUKA lightweight arm [4]. While the first was running an admittance controller using a wrist-mounted 6-axis force-torque sensor, the second was using a joint-space impedance controller to achieve joint compliance. Both implementations were using the same constraint estimator from Section 2.1.

3.1 Accrea Mobile Manipulator

The robot was operating in a kitchen environment and was able to open and close various mechanisms including cupboard doors, drawers and a microwave. Control of the orientation was resolved by setting the rotational stiffness to zero, hence realizing a damped force-follow behavior for the rotation [9]. The interaction between mobile base and manipulator was implemented according to Section 2.3. **Figure 2** shows the robot opening a cupboard door.

All mechanisms could be operated successfully in all test-runs, using the same program, without changing parameters or incorporating global knowledge about the type of the constraint (e.g. linear, circular).

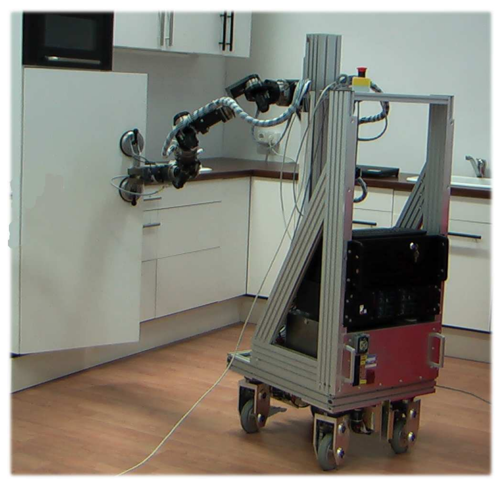

Figure 2: Accrea manipulator on omnidirectional base operating a cupboard door

3.2 KUKA LWR

To demonstrate the applicability of our approach on robots with compliant joints, the manipulator was running a joint space impedance controller. The test devices were a microwave-door and a drawer in horizontal and vertical configuration, imposing only kinematic constraints in the first case and due to the mass, additional dynamic constraints in the second case. First the approach of following the constrained trajectory, similar to [6], was implemented. While the first test case showed a success-rate of 100% with this controller and the LWR, it had serious problems

when the misalignment of Cartesian position deviation and applied force direction was large for the second test case, leading often to failure of the task.
Hence a modified version, according to (6) and (7) was implemented and showed the same good performance for both test-cases. **Figure 3** shows the LWR operating a microwave door.

Figure 3: KUKA LWR manipulating a microwave door

4 Conclusion and Outlook

We presented a general paradigm for operating unknown constrained mechanisms, based on estimation of the first-order parameter of the constrained trajectory and exploration of the kinematic constraint with the desired set-point. An exemplary velocity based implementation was introduced both for Cartesian and joint-space compliant robots and a method for incorporating a moving base into the system without changing the manipulator controller was suggested. The first working applications indicate that we are on the right track.
Even though the local estimator showed its potential in various test-cases, a careful assessment on convergence and limits of this approach has to be done in future work. For theoretic completeness the stability of the controller has to be assured and a clean solution for resolving the constraint- and manipulator-null-space has to be derived.

Acknowledgements

This work is supported in part within the DFG excellence initiative research cluster Cognition for Technical Systems - CoTeSys (`www.cotesys.org`).

References

[1] D. Bršcic, M. Eggers, F. Rohrmüller, O. Kourakos, S. Sosnowski, D. Althoff, M. Lawitzky, A. Mörtl, M. Rambow, V. Koropouli, et al. Multi joint action in cotesys-setup and challenges. *CoTeSys Cluster of Excelence: Technische Universität München & Ludwig-Maximilians-Universität München, Munich, Germany, Tech. Rep. CoTeSys-TR-10-01*, 2010.

[2] A. De Luca and C. Manes. Modeling of robots in contact with a dynamic environment. *Robotics and Automation, IEEE Transactions on*, 10(4):542–548, 1994.

[3] R. Diankov, S. Srinivasa, D. Ferguson, and J. Kuffner. Manipulation planning with caging grasps. In *Humanoid Robots, 2008. Humanoids 2008. 8th IEEE-RAS International Conference on*, pages 285–292. IEEE, 2008.

[4] G. Hirzinger, A. Albu-Schaffer, M. Hahnle, I. Schaefer, and N. Sporer. On a new generation of torque controlled light-weight robots. In *IEEE International Conference on Robotics and Automation, 2001. Proceedings 2001 ICRA*, volume 4, pages 3356–3363, 2001.

[5] N. Hogan. On the stability of manipulators performing contact tasks. *IEEE Journal on Robotics and Automation*, 4(6):677–686, 1988.

[6] A. Jain and C. Kemp. Pulling open doors and drawers: Coordinating an omni-directional base and a compliant arm with equilibrium point control. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pages 1807–1814. IEEE, 2010.

[7] T. Lefebvre, J. Xiao, H. Bruyninckx, and G. de Gersem. Active compliant motion: a survey. *Advanced Robotics*, 19(5):479–499, June 2005.

[8] E. Lutscher and G. Cheng. A Set-Point-Generator for Indirect-Force-Controlled Manipulators Operating Unknown Constrained Mechanisms . *International Conference on Intelligent Robots and Systems, IEEE (under review)*, 2012.

[9] E. Lutscher, M. Lawitzky, G. Cheng, and S. Hirche. A control strategy for operating unknown constrained mechanisms. *International Conference on Robotics and Automation (ICRA), IEEE*, pages 819–824, 2010.

[10] W. Meeussen, M. Wise, S. Glaser, S. Chitta, C. McGann, P. Mihelich, E. Marder-Eppstein, M. Muja, V. Eruhimov, T. Foote, and Others. Autonomous door opening and plugging in with a personal robot. In *International Conference on Robotics and Automation (ICRA), 2010 IEEE*, pages 729–736. IEEE, 2010.

[11] J. Sturm, A. Jain, C. Stachniss, C. Kemp, and W. Burgard. Operating articulated objects based on experience. In *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pages 2739–2744. IEEE, 2010.

[12] P. Tomei. A simple PD controller for robots with elastic joints. *Automatic Control, IEEE Transactions on*, 36(10):1208–1213, 1991.