Vetenskapsrådet

# *Application*

2015-03-31

**2015-04946** **Freidovich, Leonid** **NT-14**

## Information about applicant

**Name:** Leonid Freidovich

**Doctorial degree:** 1999-06-16

**Birthdate:** 19730704

**Academic title:** Docent

**Gender:** Male

**Employer:** Umeå universitet

**Administrating organisation:** Umeå universitet

**Project site:** Institutionen för tillämpad fysik och elektronik+

## Information about application

**Call name:** Forskningsbidrag Stora utlysningen 2015 (Naturvetenskap och teknikvetenskap)

**Type of grant:** Projektbidrag

**Focus:** Fri

**Subject area:**

**Project title (english):** Unsolved problems within robot motion control

**Project start:** 2016-01-01

**Project end:** 2019-12-31

**Review panel applied for:** NT-14, NT-1, NT-2

**Classification code:** 20202. Reglerteknik, 20201. Robotteknik och automation, 10202. Systemvetenskap, informationssystem och informatik (samhällsvetenskaplig inriktning under 50804)

**Keywords:** nonlinear control systems, robot motion control, underactuated mechanical systems, interaction force control, transverse linearization

## Funds applied for

| | | | | |
|---|---|---|---|---|
| **Year:** | 2016 | 2017 | 2018 | 2019 |
| **Amount:** | 1,524,422 | 1,375,108 | 1,467,637 | 1,448,334 |

## Descriptive data

### Project info

### Project title (Swedish)*

Olösta problem för reglering av robotrörelser

### Project title (English)*

Unsolved problems within robot motion control

### Abstract (English)*

The aim is a model-based solution for the long standing problem of simultaneous assignment of self-tuning motions of a robotic tool and of the induced interaction forces with the environment or with the object of manipulation. “Self-tuning” means that the desired trajectory is to be shaped on-line, in parallel with stabilization, and is not pre-defined as within the state-of-the-art approaches unsuccessfully used in robotics nowadays for a certain class of working scenarios.

The planned research activities include the following:

- Action 2 (12 months): Propose an approximate parametrically uncertain low dimensional mechanical model for the contacting environment and an expression for the interaction forces treated as reaction forces required to keep the (non-ideal) constraints. Derive a combined model for the robot and the environment in the form of a parametrized system of Euler-Lagrange equations with control inputs.

- Action 3 (15 months): Extend the virtual-holonomic-constraints-based motion planning technique to incorporate planning working-scenario-induced orbits satisfying requirements on the interaction forces with explicit (symbolic) dependence on the values of unknown parameters. Introduce the parameterized families of transverse linearizations using appropriate (non-minimal) sets of transverse coordinates. Design orbitally stabilizing controllers for the case of no uncertain parameters based on a (to be developed) subspace stabilization technique for linear time-varying systems.

- Action 4 (6 months): Introduce a finite-set type parametric uncertainty and design a logic-based supervisory controller, relying on measurements of the generalized coordinates and the interaction forces and torques with switching among the finite number of pre-defined sets of virtual constraints, motion generators, and the corresponding stabilizing controllers.

- Action 5 (12 months): Design a set of differential equations to change parameters of the infinite number of self-tuning sets as above, based on signals from internal and external sensors.

Various results of research activities above will be tested via numerical simulations and experiments on our prototype 7-axis robotic arm.

We expect a significant contribution to robotics brining new analytical and numerical dynamic-model-based approaches for trajectory planning, control design, and analysis for a class of nonlinear (parametrically uncertain) underactuated mechanical system systems modelling simultaneously the dynamics of a robot and of the environment or the object of manipulation.

The theory to be developed within this project is expected to lead to a breakthrough in applications of robots for automation of performing (unilateral) contact fragile operations such as assembly from details, sorting, packing, machining (e.g. automatically producing 3D shapes) using industry-standard appropriately reprogrammed robotic manipulators, equipped with appropriate tools.

At the same time, our approach has a potential to open a new research field within nonlinear control theory, where we are to propose a class of problems on orbital stabilization of self-tuning trajectories that are not pre-defined functions of time.

### Popular scientific description (Swedish)*

En trend som tydligt syns i vår vardag är att våra apparater och maskiner blir allt mer avancerade och får bättre prestanda till samma, eller kanske till och med lägre, pris genom att man kombinerar mekanisk konstruktion med elektronik och inbyggd reglering.

Kombinationen utvecklar inte bara gamla produkter utan gör det också möjligt att tillföra helt ny funktionalitet inom områden där t.ex. en ren mekanisk lösning inte varit möjlig eller varit otillräcklig.

Ett exempel är hur man kan öka säkerheten för bilar och motorcyklar med hjälp av t.ex. system för låsningsfria bromsar (ABS), något som nu finns i nästan alla moderna bilar, och hur man kan förbättra köregenskaperna genom aktiva antisladdsystem.

Inom robotiken införs nu industriellt nya tekniker som t.ex. kontaktkraftreglering för att lösa uppgifter inom bearbetning och s.k. service-robotik.

I detta projekt undersöks hur man med matematiska och reglertekniska metoder uppnår önskat beteende och prestanda hos en generell klass av mekaniska system, genom modellering av dynamiken hos en robotmanipulator med hänsyn till närvaron av en aktiv ensidig kontakt med omgivande miljö eller med ett föremål för manipulation.

Medan holonoma bivillkor på ett högre ordningens system reducerar antalet frihetsgrader och i viss mening gör det lättare att analysera, är man fortfarande tvungen att betrakta den fulla dynamiken då man har behovet av att framkalla en viss profil av interaktionskrafter, nödvändig för att utföra en uppgift enligt ett arbetsscenario.

Under det senaste decenniet har metodutvecklingen inom rörelseplanering och därtill hörande stabilisering kring önskade rörelsemönster för s.k. underaktuerade mekaniska system varit intensiv. Utifrån de metoder vi varit med att ta fram föreslår vi nu generaliseringar som skulle innebära att man även kan hantera tilldelning av inducerade växelverkande krafter, något som fortfarande utgör en teoretisk utmaning för en stor klass av dynamiska system, och som därmed avsevärt skulle öka tillämpningen inom en rad olika områden.

Tidigare har lösningar för denna klassen av problem endast kunnat approximerats genom omfattande numeriska beräkningar eller trial and error-metoden, medan den föreslagna metoden syftar till analytiska lösningar utifrån systematisk design, genom att (grovt förenklat) skriva om systemets dynamik längs med, respektive vinkelrät mot, önskade rörelsebanor och utifrån denna omskrivning karakterisera stabiliserande styrlagar. Genom detta angreppssätt får man också bra beskrivningar och möjlighet att välja styrlagar som t.ex. minimerar med avseende på parameterkänslighet från modellfel eller minimerar påverkan av yttre störningar.

## Project period

### Number of project years*

4

### Calculated project time*

2016-01-01 - 2019-12-31

## Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

|  |  |
|---|---|
| **SCB-codes*** | 2. Teknik > 202. Elektroteknik och elektronik > 20202. Reglerteknik<br>2. Teknik > 202. Elektroteknik och elektronik > 20201. Robotteknik och automation<br>1. Naturvetenskap > 102. Data- och informationsvetenskap (Datateknik) > 10202. Systemvetenskap, informationssystem och informatik (samhällsvetenskaplig inriktning under 50804) |

Enter a minimum of three, and up to five, short keywords that describe your project.

**Keyword 1***

nonlinear control systems

**Keyword 2***

robot motion control

**Keyword 3***

underactuated mechanical systems

**Keyword 4**

interaction force control

**Keyword 5**

transverse linearization

## Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

### Reporting of ethical considerations*

The reseach does not raise any ethical issues.

### The project includes handling of personal data

No

### The project includes animal experiments

No

### Account of experiments on humans

No

## Research plan

# Unsolved problems within robot motion control

## 1. Purpose and aims

Nowadays, automation using industrial robots becoming the only remedy for technology oriented businesses in highly developed regions to keep production lines from moving to countries with cheap but unsafe manual labor.  At the same time, automation provides high potential for quality improvement, efficiency, and safety of workers. However, a few key enabling technologies are still missing.

Our aim is a novel ***model-based solution*** for the long standing problem of ***simultaneous assignment of self-tuning motions of a robotic tool and of the induced interaction forces*** with the environment or with the object of manipulation. Here, “self-tuning” means that the desired trajectory is to be shaped on-line, in parallel with stabilization, and is not pre-defined.

The need for this development can be seen from the following observation. Even in the highly automated automotive industry, there are *no robots used in the assembly operations involving contact of parts with different stiffness properties*. The reason for this is an **unsolved theoretical problem** within robot motion control leading to the absence of technology for industrial operations requiring simultaneous control of the posture of a robotic manipulator tool and of the force induced by its motion on contact with a deformable fragile environment. Although currently there is no technology for industrial robots even to ensure accuracy of following pre-defined contactless motions with errors less than a few millimeters, as soon as a contact is required, the robot manufacturers and system integrators are out of reliable options.

To confirm this, despite a huge number of research papers and monographs devoted to robot interaction force control, even the most advanced state-of-the-art software, e.g. produced by ABB Robotics, provides only a compromising solution requiring from the designers to choose a particular precision either in the tool velocity assignment or in the value of a constant inflicted force, see e.g. [ABB]. This limitation, as well as other shortcomings of this software package and similar ones, prevents the use of industrial robots in operations with fragile contacts, as well as, e.g., in various metal handling problems, where extremely expensive (and severely restricted in the size of the workspace) CNC machines totally dominate the market.

*We believe that **our new approach will allow handling contact interactions without sacrificing accuracy achievable within contactless operations.***

The key novel mathematical (technical) features of the proposed approach are the following.

1. A robot and the object of manipulation are to be treated as a single combined *underactuated mechanical system* with unknown parameters. Here we are to exploit recent advances within motion planning and control design for this class of systems.
2. A parametrized family of motions equipped with orbitally stabilizing controllers is to be designed using an extension of a recently developed by the applicant and co-workers technique known as *virtual-holonomic-constraints*-based motion planning and *transverse-linearization*-based feedback control design. The required extension is related to handling parametric uncertainty in the description of the interaction.

3. A total *disturbance compensator* and a *self-tuning motion generator* with a stabilizing feedback control law are to be designed to complement and to orchestrate transitions between the controllers in the family, respectively, exploiting, in particular, signals from contact torque/force sensors to correct identification errors of the parameters of the model.

While the key theoretical contribution is expected within the mature field of *nonlinear control system* design, there are two nonstandard ingredients in the problem formulation inspired by the robotic applications: First, we are to look for *orbital stabilization* instead of classical time-reference trajectory tracking problem. Second, we are to *change the reference orbit on-line based on the sensor signals*.

While the first modification has being already (recently) suggested by the applicant and co-authors, it is important to realize the need for the second one, defined by the *fundamental challenge* of the motivating application at hand. It is easy to realize, that as soon as a robot and an object of manipulation are in contact, the interaction forces become the internal reaction forces induced by the contact-keeping constraints. Hence, they cannot be planned independently since the (ideal) *reaction forces are unambiguously defined by the values of the system configuration variables and their derivatives*, while small errors in the nominal values of the parameters as well as in these variables result in huge errors in the induced forces.

## 2. Survey of the field

Search for intelligent behaviours of mechanical systems, and methods to create them are the two fundamental challenging problems in classical and modern control theory [Kha02], computer science [Lav05], robotics [Spo05], as well as in classical and celestial mechanics. There are solutions for a few particular subclasses, see e.g. [Spo05] and [Lav05] for overviews; but there are currently no common approaches applicable in general settings.

One of the key (mathematical) challenges for this project is working with the class of ***mechanical systems*** [App53, Arn88] with controls [Beg22, Kha02, Blo03] when the number of the degrees of freedom (the number of generalized coordinates) is less than the number of independent controlled generalized forces. Systems in this class are called ***underactuated*** [Spo98, Liu13]; they are common for applications (note that just directly modelling flexibility immediately leads to underactuation). The most difficult among the underactuated systems to approach are those that are not fully feedback linearizable and non-minimum phase [Kha02]. For them, nonlinearities in dynamics cannot be removed by a feedback action (or/and a change of variables) even in a vicinity of a particular nontrivial feasible trajectory. Moreover, such trajectories are hard to find. In practice, trajectory planning and motion stabilization tasks for such mechanical systems are typically solved *ad hoc* exploiting special features of particular examples; see, however, our promising preliminary result [Shi14].

We arrive at the necessity to handle such nonlinear systems (with passive degrees of freedom) following the key idea of this project: ***To model the environment or the object of manipulation as another (parametrically uncertain) mechanical system***, connected to the mechanical system describing dynamics of the manipulator through ideal or non-ideal holonomic constraints, see e.g. [Udw05], and avoiding the nowadays common approach of describing interaction by *ad hoc* models of the resistive force from the environment due to interaction, see e.g. the classical monographs on the subject [Gor97, Sic99, Nat03], descriptions from the relevant patents, such as [P1, P2, P3, P4], as well as in the large amount of articles that can be easily found searching for “robot force control” in any standard research database (and discarding the works related to haptics, where this term has a different meaning), see also an overview in [Vil08].

A conclusion from studying a vast number of results presented in monographs, patents, and many research articles is as follows. To the best of our knowledge, the idea to base a control design on a mechanical model combining description of dynamics of the robot and of the object of interaction (in the form of Euler-Lagrange equations of first kind, see e.g. [Udw05] merged with [Blo03]) has not being used before. In fact, in all the studied sources, the model of interaction is always simplified assuming that one can ignore the internal mechanical feedback imposed by the impact of the robot on the environment, i.e. the fact that the action of the robot induces deformation of the environment, with not infinite inertia and stiffness, resulting in a dynamic change of the directions of the interaction forces.

This state-of-the-art approach leads to

a. A significant simplification of the model by dropping dynamics of the degrees of freedom related to the dynamics of the environment and making an unavoidable empiric assumption on the law defining the reaction force to be, e.g., proportional to the normal displacement of the end-point of the tool with respect to the initial orientation of the contact surface (“a resistive environment”) or similar.

b. Searching only for a restrictive class of feedback controllers that are less sensitive to the properties of the environment at the expanse of severe limitations on achievable accuracies in terms of both posture tracking and contact force assignment errors.

As a result, there are following two commonly used ideologies for designing controllers for industrial applications, see e.g. [Gor97, Sic99, Nat03, Vil08]:

1. The impedance/compliance control approach (together with many modifications proposed after the Hogan’s seminal contribution [Hog85]), aiming at making the robot dynamics react on the environmental force approximately as a (simple linear) mechanical system of a prescribed (mass-damper-spring) structure. Here, planning desired motions and forces is avoided. Analysis of the patents by major robot manufactures leads us to a conclusion that this is the only approach used in commercially available software.
2. Various force/position, hybrid or parallel feedback designs that allow to approximately follow an appropriately planned time evolution of the postures in some fixed specified directions and of the induced forces in the other directions leaving the full response of the system in terms of coordinates and forces not only unpredictable but possibly even dependent on the initial conditions. Note that here infinite stiffness or infinite inertia of the environment along particular (frozen!) directions is assumed.

Obviously, these two commonly accepted state-of-the-art techniques in principle cannot provide a solution whenever the mentioned approximate models of the interactions are inappropriate. The goal of this project is to develop foundation of a new *mathematically justified theory aimed at simultaneous assignment of self-tuned robotic tool motions and of the induced interaction forces with the environment* or with the object of manipulation based on a more accurate parametrically uncertain model. There are several reasons why this approach has not (to the best of our knowledge) being attempted by other researchers and why we believe we will succeed, provided the application is supported; they include the following:

- Motion planning and design of control laws for underactuated mechanical systems are challenging tasks, where a promising breakthrough has being recently achieved by the applicant and co-workers; see e.g. [Fre09, Fre09b, Shi10, Fre11, Shi14]. The key contribution is the technique known as virtual-holonomic-constraints-based motion planning and transverse-linearization-based feedback control design.
- While kinematical and dynamical parameters of the robot may be identified and calibrated prior to the execution of a work scenario, identifying parameters of the environment must

be done on-line, based on signals from (external and internal) sensors. At the same time, since the parameters describing the interaction are not known in advance, it is in principle not possible to generate a feasible desired trajectory of the robot as a pre-defined function of time. Hence, the whole power of the modern control theory is useless since the key state-of-the-art assumption is the knowledge of a feasible desired trajectory to stabilize.

- While changing directions and magnitudes of the induced interaction forces must be sensed on-line, some of these forces must be compensated. We are to use the recently becoming popular technique known as active disturbance rejection control, see e.g. [Fre08] for the extended-high-gain-observer-based approach, which we are to follow.

# 3. Project description

## *3.1 Class of models*

In this project we are to study the class of models described by nonlinear constrained (of first kind, i.e. with Lagrange multipliers) ***Euler-Lagrange system*** of (descriptor) ordinary differential equations with assignable inputs, see e.g. [Udw05] merged with [Blo03]. As stated above, we are to assume that parameters of the model describing the robot are identified, while there are unknown parameters of a simplified mechanical model describing dynamics of the environment and the inducible interaction forces. The parameters are to include, in particular, a finite inertia, a finite stiffness, and friction coefficients.

## *3.2 The core theoretical ideas*

The key observations to approach trajectory planning and control design for underactuated systems to be used are the following.

For any given periodic or finite-time trajectory of a dynamical system there exists a reduced-order dynamical system in a form of a differential equation for a single scalar variable, such that the time evolution of *the states of the full-order system along this particular motion can be generated from the time-evolution of this variable*. In biology-inspired robotics, such a reduced system is called *motion generator* [Hol06]. For systems rewritten in the standard Isidori-normal form, such a variable can be found analytically and (at least locally) chosen as one of the states of the base of one of the chains of integrators. For example, for underactuated mechanical systems it can be taken as one of the generalized coordinates (note that only directly actuated degree of freedom can be transformed into independent double integrators of the inputs; so, this property is quite intriguing!); see our ground stating work in [Shi10] for details for the case of a class of holonomic mechanical systems without interactions with the environment. Within this project we are to develop this idea to the case of extended models (including a simplified dynamics of the environment and of interaction forces) including parametric uncertainty and a mathematical description of dependence of the measured interaction forces on such parameters.

Existence of a motion generator immediately leads to existence of a family of piecewise smooth “geometrical” relations among the “bottom variables” of the chains of integrators and the other states that are valid along a feasible motion. Knowledge of these relations, called ***virtual holonomic constraints*** or servo-constraints in the contents of Euler-Lagrange systems, is instrumental for analysis of dynamics in a vicinity of a target motion.

These relations, that are valid along a particular feasible solution, can be used for a straightforward introduction of new state variables that identically vanish along it. Due to presence of chains of integrators, several other vanishing variables can be obtained by differentiation. As a result, one obtains a set of new states that are orthogonal to the particular solution. Typically, the number of obtained in such a way independent quantities is insufficient (less by at least one than the order of the system) and it is necessary to find the remaining orthogonal independent state variable and its dynamics. Apparently, this variable can be chosen as a conserved quantity for the one-degree of freedom system obtained projecting the dynamics onto the constraints. In essence, this is what is done with the class of underactuated holonomic mechanical systems in [Shi10] for the case of no parametric uncertainty. The fact that this is possible for a larger class of systems can be seeing from the main contribution of our preliminary study partially reported in [Fre11].

Finding parametrized families of variables vanishing along a specific parametrized motion (they automatically become transversal, in fact orthogonal, to the motion) can be interpreted as a constructive procedure for defining a moving Poincaré section [Leo06] in new coordinates that can be computed as deviations from the synchronous motion consistent with the virtual constraints (note that the virtual constraints do not impose any restrictions on the initial conditions and their number is always equal to $(n-1)$, where $n$ is the total number of the degrees of freedom of the combined dynamical model. Remarkably, for some classes of mechanical systems it is possible to compute a linearization for the dynamics of the transverse coordinates defined in such a way analytically [Fre09, Fre09b, Shi10, Fre11, Gus15]. We strongly believe it can be done within this project for the class of systems described above. The (semi-) analytically computable linearization will take the standard form (with some particular additional structure)

$$\dot{x} = A(t,p)\, x + B(t,p)\, u\,, \qquad y = C(t,p)x\,,$$

where $x$ is at least a $(2n-1)$-dimensional vector of linear variations of the transverse coordinates and $y$ is a vector of linear variations of the measured outputs (physically provided by the encoders and the force/torque sensor integrated into the arm before the tool-changer). In contrast to our previous published results, this system will have uncontrollable subspaces (consistent with feasible initial conditions!) that are absent in the holonomic case without interaction at contacts, see the preliminary result reported in [Fre11] and [Gus15]. We will rigorously prove during the work on this project that finding an exponentially stabilizing linear feedback for an appropriate subspace of this linear control system will lead to a construction of an orbitally exponentially stabilizing controller for the original system in a similar way as for the systems without conserved quantities studied by us earlier. This leads to a new class of control problems. The challenging problem of subspace stabilization will be investigated within this project.

At the same time, since the matrices above will depend on unknown values of the parameters $p$ in a very sophisticated way: through parameter dependent holonomic constraints and solution of the parameter-dependent motion generator, we need to find a strategy to orchestrate transition among orbitally stabilizing controllers from the parametric family. The nonstandard challenge here is that we are to search not only for adaptation of the parameters of a feedback controller to achieve stabilization of a pre-defined motion but for a feasible motion itself. We are to start with the case of a finite set of possible values of parameters following the ideas of designing higher-level logic-based switching supervisor as in the applicant's Ph.D. thesis [Fre05] and after that proceed with handling the uncountable case.

It should be mentioned that for a large class of target motions, even in mechanical systems, the geometric relations among the chosen states cannot be defined globally. However, conceptual arguments allow discovering that any trajectory defined on a finite time interval can be split into a finite number of pieces such that a smooth parameterization via geometric relations does exist for each of them separately. Moreover, in particular, they can be easily computed using the intervals, on which one of the base states changes monotonically (see our pre-study result reported in [Fre09] for details in the case of impulsive mechanical systems). It is expected that, in general, the linearization of the dynamics orthogonal to the chosen motion can be always constructed as a linear time-dependent system with piecewise smooth coefficients and, possibly, state updates at particular time moments, that is an impulsive linear control system. To the best of our knowledge, methods for subspace stabilization of such systems have not been considered; we are to develop them.

Another direction of research will be the following. The classical approaches to achieve reduction of sensitivities with respect to disturbances is redesigning nominal controllers to enhance robustness, designing estimators for disturbances, in particular, the ones due to imperfect cancellation of terms by feedback controllers imposing a motion, and observers for unmeasured states, such as robust differentiators for estimating velocities. Dealing with these issues using high-gain observers and high-gain disturbance estimators is within another field of expertise of the applicant; the results of [Fre08] have strong potential to be extended and merged with control design technique based on computation of dynamics for the states orthogonal to the target solution.

### 3.3 Time table and implementation

The main applicant is expected to devote at least 20% of his time to research within this project. A new Ph.D. student will be hired to work on this project full time. We also need to finance traveling, collaboration, and dissemination related expenses to cover presentations on international conferences and external lectures, research visits, and publication fees.

Although continuation of on-going collaborations is expected (please see Section 7 below), possible contributions from other researchers are expected not to be crucial for the success of this project.

The following (overlapping) basic research and experimental activities are tentatively planned for this 48-month project in the case of approval.

Action 1 (first 9 months): Design a low dimensional numerical benchmark model for testing the proposed approach and for verifying advantages comparing with the other state-of-the-art methods. Perform system identification experiments for our 7-DoF robotic arm hardware set-up, develop a simulation model, and design an interaction scenario (emulating assembly of fragile parts) with the corresponding hardware modifications.

Action 2 (12 months): Propose an approximate parametrically uncertain low-dimensional mechanical model for the contacting environment and an expression for the interaction forces treated as reaction forces required to keep the (non-ideal) constraints. Derive a combined model for the robot and the environment in the form of a parametrized system of Euler-Lagrange equations with control inputs.

Action 3 (15 months): Extend the virtual-holonomic-constraints-based motion planning technique to incorporate planning working-scenario-induced orbits satisfying requirements on the interaction forces with explicit (symbolic) dependence on the values of unknown parameters. Introduce the parameterized families of transverse linearizations using appropriate (non-minimal) sets of transverse coordinates. Design orbitally stabilizing controllers for the case of no uncertain parameters based on subspace stabilization ideas for linear time-varying systems.

Action 4 (6 months): Introduce a finite grid-based parametric uncertainty and design a logic-based supervisory controller, relying on measurements of the generalized coordinates and the interaction forces and torques with switching among the finite number of pre-defined sets of virtual constraints, motion generators and the corresponding stabilizing controllers. Test performances of the proposed algorithms in simulations and, possibly, in experiments.

Action 5 (12 months): Design a set of differential equations to change parameters of the infinite number of self-tuning sets as above, based on signals from internal and external sensors. Test performances of the proposed algorithms via numerical simulations.

Action 6 (last 6 months): Generalize the obtained results to propose a control theory with self-tuning target trajectories for a class of parametrically uncertain nonlinear systems with outputs and manifold-like descriptions of the desired motions.

### *3.4 Collaboration and project continuation plan*

As soon as some promising theoretical results and some experimental confirmations are achieved, it is planned to proceed with similar tests in industrial settings using facilities of

- The robotic lab at NTNU (Trondheim, Norway), according to our preliminary collaboration agreement with the group of Professor A. Shiriaev, and
- The robotic lab at LTH (Lund, Sweden), according to our preliminary collaboration agreement with the group of Professor R. Johansson and Professor A. Robertsson.

In both labs, a unique software, developed within a previous EU project, for direct low level feedback control law assignment in standard industrial robots, produced by ABB Robotics, is implemented and used (with a permission from ABB). The first lab is also equipped with precise external to the robot measuring system by Nikon, which costs more than half of the total budget of this project.

It is also planned to use support for this project from VR as co-financing for an EU project. Currently we are discussing participating in such a project with a tentative title “Advanced computational robotics tools for human gait analysis and lower-limb prosthetic design”. Here the methods developed within this project are expected to be applied for design of active and passive prosthesis for human rehabilitation. There, it is necessary to control various internal forces simultaneously with staying close to an orbit defined by a walking pattern.

## 4. Significance

We expect a significant contribution to the progress with nowadays unsolved problems in robotics brining new analytical and numerical dynamic-model-based approaches for nonstandard trajectory planning, control design, and analysis of a very challenging but important for applications class of general restricted controlled mechanical systems. In addition, our approach will open a way for semi-analytical computational investigation of robustness with respect to parametric uncertainties and design of robustifying additions to nominal feedback controllers. This is crucial for applications but, to the best of our knowledge, has not been attempted before, being impossible to approach within the current state-of-the-art frameworks.

More importantly, we believe that the theory to be developed within this project would lead to a breakthrough in application of robots for automation of performing (unilateral) contact operations such as assembly from details, sorting, packing, machining (e.g. automatically producing 3D shapes) using industry-standard appropriately reprogrammed robotic manipulators, equipped with appropriate tools.

At the same time, our approach has a potential to open a new research field within nonlinear control theory, where we are to propose a class of problems on orbital stabilization of self-adjusted trajectories that are not pre-defined functions of time.

## 5. Preliminary results

The study will be grounded on the recent results obtained by the applicant and co-workers, the key ideas of which are briefly outlined above (please see Section 3.2 and the ending of Section 2), i.e. following the combined virtual holonomic constraints and transverse linearization techniques; see [Beg22, Ura67, Mag13] and our works [Shi05, Wes07, Shi08, Shi09, Fre09, Fre09b, Shi10, Fre11, Gus15] for details.

On the other hand, a few practical experimental case studies have being performed by the applicant and his collaborators, some of them are reported in [Val11, Sto12, Sor12, Lin13, Jon13], to identify possible automation scenarios of interest, where force control is useful. Limitations of currently known techniques are confirmed during our experimental studies.

## 6. Equipment

Experiments will be done on a 7-DOF light-weight manipulator (LWA4) by Schunk with open control interface equipped with special electronics produced by dSpace for rapid control system prototyping and with an integrated force-torque sensor that will be used for experimental studies of constrained motions during implementation of manipulation tasks. Please see [Schunk] for some details on the hardware set-up.

## 7. International and national collaboration

The research network of the applicant is large and active (please see the attached applicant's CV). For this project, scientific input from *Anton S. Shiriaev (Norwegian University of Science and Technology, Norway), Rolf Johansson* and *Anders Robertsson (Lund University), Christine Chevallereau* and *Yannick Aoustin* (Ecole Centrale de Nantes, France), *Mark W. Spong* (University of Texas at Dallas, USA), and *Giuseppe Oriolo* (Università di Roma, Italy) shall be most valuable. We also plan to continue collaboration with *Sergei V. Gusev* (St. Petersburg University, Russia) in relation to numerical SDP-based approach for stabilization of linear periodic systems (to extend results of [Gus07,Gus10]), and with *Hassan K. Khalil* (Michigan State University, USA) in relation to robust state and disturbance observer designs [Fre08]. However, possible contributions from these researchers are not considered essential for the success of this project.

## 8. SWOT risk analysis

We believe that this project has medium to high risk of failure. Here is a brief analysis.

- ***Strengths***: The applicant is an expert in the field of this proposal (strong theoretical knowledge within nonlinear control systems, analytical mechanics, and robotics) and, in fact, the project is heavily based on the applicant's competence and previous results obtained in collaboration with leading experts in the field. The applicant's group is already involved in collaboration projects with industrial partners, including Ålö AB.
- ***Weaknesses***: The applicant's current research group is weakly connected to robotic manufactures and robotic systems' integrators. There is no strong competence in software development and complex system identification tasks. No prior experience working with CAN communication protocols (and related limitations) used in the current hardware set-up.
- ***Opportunities***: Even partial solutions and successful completion of some of the planned research tasks may result in significant impact on the field (please see Section 4 above).
- ***Threats***: There are currently no strong candidates for the associated Ph.D. student position. Many things can go wrong working with hardware, while results of such a project without experimental validation may be significantly reduced in the value.

The issues mentioned above will be taken into account during the process of hiring a Ph.D. student and will influence the applicant's future decisions about the level of involvement of other researcher colleagues into the project in case of approval and support from VR.

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## Interdisciplinarity

### My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

## Scientific report

### Scientific report/Account for scientific activities of previous project

## Budget and research resources

## Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

### Dedicated time for this project

| | Role in the project | Name | Percent of full time |
|---|---|---|---|
| **1** | Applicant | Leonid Freidovich | 20 |
| **2** | Other personnel without doctoral degree | a new Ph.D. student | 100 |

### Salaries including social fees

| | Role in the project | Name | Percent of salary | 2016 | 2017 | 2018 | 2019 | Total |
|---|---|---|---|---|---|---|---|---|
| **1** | Applicant | Leonid Freidovich | 20 | 178,561 | 183,918 | 189,436 | 195,119 | 747,034 |
| **2** | Other personnel without doctoral degree | a new Ph.D. student | 100 | 477,845 | 496,959 | 516,837 | 537,511 | 2,029,152 |
| | Total | | | 656,406 | 680,877 | 706,273 | 732,630 | 2,776,186 |

## Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

## Premises

| | Type of premises | 2016 | 2017 | 2018 | 2019 | Total |
|---|---|---|---|---|---|---|
| 1 | local costs (7%) | 75,418 | 68,031 | 72,609 | 71,654 | 287,712 |
| | Total | 75,418 | 68,031 | 72,609 | 71,654 | 287,712 |

## Running Costs

| | Running Cost | Description | 2016 | 2017 | 2018 | 2019 | Total |
|---|---|---|---|---|---|---|---|
| 1 | Attending conferences | twice a year | 60,000 | 60,000 | 60,000 | 60,000 | 240,000 |
| 2 | Laptop and accesories | for the Ph.D. student | 10,000 | 0 | 0 | 0 | 10,000 |
| 3 | Operational expences | - | 5,000 | 5,000 | 5,000 | 5,000 | 20,000 |
| 4 | Hardware | modifications of the robot | 120,000 | 0 | 40,000 | 0 | 160,000 |
| 5 | Open access | TAC fees | 226,000 | 226,000 | 226,000 | 226,000 | 904,000 |
| | Total | | 421,000 | 291,000 | 331,000 | 291,000 | 1,334,000 |

## Depreciation costs

| Depreciation cost | Description | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|

## Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

## Total budget

| Specified costs | 2016 | 2017 | 2018 | 2019 | Total, applied | Other costs | Total cost |
|---|---|---|---|---|---|---|---|
| Salaries including social fees | 656,406 | 680,877 | 706,273 | 732,630 | 2,776,186 | | 2,776,186 |
| Running costs | 421,000 | 291,000 | 331,000 | 291,000 | 1,334,000 | | 1,334,000 |
| Depreciation costs | | | | | 0 | 886,917 | 886,917 |
| Premises | 75,418 | 68,031 | 72,609 | 71,654 | 287,712 | | 287,712 |
| Subtotal | 1,152,824 | 1,039,908 | 1,109,882 | 1,095,284 | 4,397,898 | 886,917 | 5,284,815 |
| Indirect costs | 371,598 | 335,200 | 357,755 | 353,050 | 1,417,603 | | 1,417,603 |
| Total project cost | 1,524,422 | 1,375,108 | 1,467,637 | 1,448,334 | 5,815,501 | 886,917 | 6,702,418 |

## Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

### Explanation of the proposed budget*

Items in the applied budget:

- Expenses for attending 2 international conferences per year (registration fee, airfares, logging) — 60 kSEK p/year + OH;
- Operational expenses, which include purchasing books and copies of scientific articles etc. — 5 kSEK p/year + OH;
- Miscellaneous mechanical parts, electronics and software licenses for fast control prototyping system (based on dSpace MABX II with hardware/software bundle allowing interface to two CAN busses) for the 7-axis robotic arm LWA4 by Schunk — 120 kSEK + OH in 2016 and the — 40 kSEK + OH in 2018.
- Payment for 2 open-access articles published in a prestigious peer-review journal each year — 3500 USD p/year (based on the current published IEEE Open Access fee for IEEE Transactions on Robotics);
- New laptops and accessories for the new student — 10 kSEK + OH.

Other financial resources of the project include:

- The existing hardware equipment purchased especially for this project mostly from the applicant's local Umeå University grants. The already paid costs are the following: 737,500 SEK (the arm with open control interface produced by Schunk) + 7,132 SEK (safety related modification) + 142,339 SEK (rapid control prototyping hardware/software bundle produced by dSpace) = 886,917 SEK (total).

## Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

## Other funding for this project

| Funder | Applicant/project leader | Type of grant | Reg no or equiv. | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|---|---|---|

## CV and publications

### CV

# CV / scientific qualifications

## 1. Higher education degree

- **M.Sc. in Engineering:** *February 1996* – Department of Mechanics and Control Processes, *St. Petersburg State Technical University*, Russia.

## 2. Doctoral degrees

- **Kandidat of Physical and Mathematical Sciences:** *June 1999* – Department of Mechanics and Control Processes, *St. Petersburg State Technical University*, St. Petersburg, Russia; thesis: "Stability and Control of Robotic Manipulators"; supervisor: Prof. A.A. Pervozvanski.
- **Ph.D. in Mathematics:** *March 2005* – Department of Mathematics, *Michigan State University*, USA; thesis: "Logic-Based Switching Control of Nonlinear Systems Using High-Gain Observers"; supervisor: Prof. H.K. Khalil.

## 3. Postdoctoral positions – *none (nonstandard career path: two Ph.D. degrees instead of post-doctoral positions)*

## 4. Qualification as an associate professor

- **Docent in Control Systems:** *October 2010* – Faculty of Science and Technology, Umeå University, Umeå, Sweden.

## 5. Current position

- **Associate Professor** [universitetslektor]: since March 2009, permanent (tillsvidareanställning), share of time spent in research is 80% until the end of 2015, Department of Applied Physics and Electronics, Umeå University, Umeå, Sweden.

## 6. Previous positions and periods of appointment

- **Assistant Professor** [forskarassistent]: *March 2005 – March 2009*, Department of Applied Physics and Electronics, Umeå University, Umeå, Sweden.
- **Graduate Research Assistant** (part-time): *December 2004 – March 2005*, Department of Electrical and Computer Engineering, Michigan State University, East Lansing, USA.
- **Graduate Teaching Assistant** (half-time): *August 1997 – March 2005*, Department of Mathematics, Michigan State University, East Lansing, MI, USA.
- **Research Assistant** (part-time): *1993 – 1997*, Department of Mechanics and Control Processes, St. Petersburg State Technical University, St. Petersburg, Russia.
- **Research Assistant** (part-time): *1994 – 1995*, State Scientific Centre, Central Research and Design Institute for Robotics and Technical Cybernetics, St. Petersburg, Russia.

## 7. Interruptions in research

- Parental leaves (approx. 3 months): May 22 – June 1, 2007; August 1 – 31, 2008; September 22 – 30, 2008; October 1 – 14, 2010, June 11 – August 6, 2012.

## 8. Supervision (main advisor, completed)

- Stanislav Aranovskiy, post-doc: 2012-2014.

## 9. Supervision (co-advisor, completed)

- Uwe Mettin: December 2009 (main advisor: Prof. Anton Shiriaev),

- Pedro Xavier Miranda La Hera: March 2011 (main advisor: Prof. Anton Shiriaev),
- Daniel O. Morales: January 2015 (main advisor: Prof. Anton Shiriaev),

## 10. Active supervision duties (on-going)

Currently, I am the main advisor for 2 Ph.D. students (Szabolcs Fodor and I Yung Ong) and 1 post-doc (Carlos Vázques).

## 11. Scientific outcome (1996-2015):

- **35** peer-reviewed journal articles; **58** peer-reviewed international conference contributions; **2** books and **2** book chapters.
- Google scholar page: http://scholar.google.com/citations?user=VBekdAUAAAAJ

## 12. Fields of research expertise / interests

(A) Control Design for Nonlinear Systems; (B) Stability Analysis for Nonlinear Systems; (C) Robot Control and Robotics; (D) Feedback Control of Mechanical Systems; (E) Design of Observers; (F) Trajectory Planning for Underactuated Mechanical Systems.

## 13. Research network and main research collaborators

• ***Prof. Anton S. Shiriaev***, Norwegian University of Science and Technology, Norway and Umeå University, Sweden (same research group in 2005-2010); • ***Prof. Anders Robertsson***, LTH, Lund University, Sweden (visited: August 28-31 and November 13-18, 2005, June 26-30 and August 25-31, 2006); • ***Prof. Rolf Johansson***, LTH, Lund University, Sweden (visited: same as for A. Robertsson); • ***Prof. Hassan K. Khalil***, Michigan State University, USA (Ph.D. and M.Sc. advisor); • ***Dr. Ilya V. Burkov***, St. Petersburg State Polytechnic University, Russia (M.Sc. co-advisor); • ***Prof. Francisco Gordillo***, University of Seville, Spain (visited: May 17-23, 2010); • ***Dr. Fabio Gómes-Estern***, University of Seville, Spain; • ***Prof. Mark W. Spong***, University of Texas at Dallas, USA; • ***Dr. Sergei V. Gusev***, St. Petersburg State University, Russia; • ***Prof. Leonid M. Fridman***, Universidad Nacional Autónoma de México, Mexico (visited: June 1-July 31, 2010); • ***Prof. Jakob Stoustrup***, Aalborg University, Denmark (visited: August 14-24, 2006); • ***Prof. Takayuki Takahashi***, Fukushima University, Japan (visited: August 17-19, 2007 and March 15-22, 2008); • ***Dr. Christine Chevallereau***, Institut de Recherche en Communications et Cybernétique de Nantes, France (visited: September 24-29, 2007); • ***Prof. Alexander L. Fradkov***, Institute for Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, Russia; • ***Dr. Giuseppe Oriolo***, Università di Roma, Italy; • ***Dr. Denis Efimov***, INRIA, Lille, France.

## 14. Honors and Awards

• Track Programme Committee (TPC) member for the three IEEE Emerging Technologies and Factory Automation Conferences: Italy 2013, Spain 2014, and Luxemburg 2015; • Steering Committee (SC) members for the IEEE/IES International Conference on Mechatronics, Japan 2015; • International Programme Committee (IPC) member for the 14th Mechatronics Forum International Conference, Sweden 2014; • Senior member of IEEE (2011); • IPC member for the 11th International Workshop on Variable Structure Systems, Mexico 2010; • Travel grant from Swedish Research Council to visit UNAM; • Career grant "Young Researcher Award" (Karriärbidrag) from Umeå University, 2009-2011; • Selected into the final list of 5 for 2009 Guan Zhao-Zhi Award; • Best presentation award on 2009 American Control Conference; • Scholarships from Open Society Institute (International Soros Science Education Program, grants a97-1503 and s96-2061), 1997 and 1996; • Reviewer for MathSciNet and for many international journals and conferences within the fields of Control Systems and Robotics.

## Publication list

# Leonid B. Freidovich's publications

Citation information below is given based on ***Google Scholar*** (on 2015-03-26). However, the numbers of self-citations have been subtracted after manually review of all the listed citing articles.

*The list below contains publications only for the last 8 years, i.e. for 2008–2015 with indicated numbers of external citations. The five most cited publications during the whole active research period (1996–2015) are listed at the end.*

*The five most important publications for the project are marked with* **(*)**; *they are:* [J1], [J4], [J14], [J18], *and* [C10].

## 1. Peer-reviewed original articles (2008-2015)

[J1] **(*)** S.V. Gusev, L.V. Paramonov, S.S. Pchelkin, A. Robertsson, L.B. Freidovich, and A.S. Shiriaev, "On modification of PD+ controller for orbital stabilization of mechanical systems," *PMM Journal of Applied Mathematics and Mechanics* (Translation of the Russian Journal *Prikladnaya Matematika i Mekhanika*), to appear in 2015.

[J2] D.O. Morales, P.X. La Hera, S. Westerberg, L.B. Freidovich, and A.S. Shiriaev, "Path-constrained motion analysis. An algorithm to understand human performance on hydraulic manipulators," *IEEE Transactions on Human-Machine systems*, vol. 45, no. 2, pp. 187–199, 2015. [http://dx.doi.org/10.1109/THMS.2014.2366873; number of citations: **0**].

[J3] S. Pchelkin, A. Shiriaev, L. Freidovich, U. Mettin, S. Gusev, W. Kwon, and L. Paramonov, "A dynamic human motion: coordination analysis," *Biological Cybernetics*, vol. 109, no. 1, pp. 47–62, 2015. [http://dx.doi.org/10.1007/s00422-014-0624-4; number of citations: **0**].

[J4] **(*)** A.S. Shiriaev, L.B. Freidovich, and M.W. Spong, "Controlled invariants and trajectory planning for underactuated mechanical systems," *IEEE Transactions on Automatic Control*, vol. 59, no. 9, pp. 2555–2561. [http://dx.doi.org/10.1109/TAC.2014.2308641; number of citations: **0**].

[J5] D.O. Morales, S. Westerberg, P.X. La Hera, U. Mettin, L. Freidovich, and A.S. Shiriaev, "Increasing the level of automation in the forestry logging process with crane trajectory planning and control," to appear in *Journal of Field Robotics*, 2014 [http://dx.doi.org/10.1002/rob.21496; number of citations: **7**].

[J6] A.S. Shiriaev, L.B. Freidovich, and M.W. Spong, A remark on controlled Lagrangian approach," *European Journal of Control*, special issue on "Lagrangian and Hamiltonian Methods for Nonlinear Control", vol. 19, no. 6, pp. 438–444, 2013. [http://dx.doi.org/10.1016/j.ejcon.2013.09.004; number of citations: **1**].

[J7] S.V. Aranovskiy and L.B. Freidovich, “Adaptive compensation of disturbances formed as sums of sinusoidal signals with application to an active vibration control testbench,” *European Journal of Control*, special issue on “Benchmark on adaptive regulation: rejection of unknown/time-varying multiple narrow band disturbances”, vol. 19, no. 4, pp. 253–265, 2013. [http://dx.doi.org/10.1016/j.ejcon.2013.05.008; number of citations: **4**].

[J8] S.V. Aranovskiy, L.B. Freidovich, L.V. Nikiforova, and A.A. Losenkov, “Modeling and identification of dynamics in a hydraulic actuator with a spool valve. Part I: Modeling / Part II: Identification,” Scientific and Technical Journal «Priborostroenie», vol. 56, no. 4, pp. 52–56 / 57–60, 2013 (in Russian). [http://pribor.ifmo.ru/en/article/1270/ / http://pribor.ifmo.ru/en/article/1271/; number of citations: **0**]

[J9] P.X. La Hera, A.S. Shiriaev, L.B. Freidovich, U. Mettin, and S. Gusev, “Stable walking gaits for a three-link planar biped robot with one actuator,” *IEEE Transactions on Robotics*, in vol. 29, no. 3, pp. 589–601, 2013. [http://dx.doi.org/10.1109/TRO.2013.2239551; number of citations: **4**].

[J10] L.T. Aguilar, I. Boiko, L. Fridman, and L.B. Freidovich, “Generating oscillations in inertia wheel pendulum via two-relay controller,” *International Journal of Robust and Nonlinear Control* , vol. 22, no. 3, pp. 318–330, 2012. [http://dx.doi.org/10.1002/rnc.1696; number of citations: **6**].

[J11] I.M. Meza-Sancheza, L.T. Aguilar, A.S. Shiriaev, L.B. Freidovich, and Y. Orlov, “Periodic motion planning and nonlinear H-infinity tracking control of a 3-DOF underactuated helicopter,” *International Journal of Systems Science*, vol. 42, no. 5, pp. 829–838, 2011 (invited paper for the special issue on “New advances in H-infinity control and filtering for nonlinear systems.”) [http://dx.doi.org/10.1080/00207721.2010.517874; number of citations: **17**].

[J12] A.S. Shiriaev, L.B. Freidovich, R. Johansson, and A. Robertsson, “Global stabilization for a class of coupled nonlinear systems with application to active surge control,” *Dynamics of Continuous, Discrete and Impulsive System*, vol. 17 (B), no. 6, pp. 875–908, 2010 (invited paper for the special issue in honor of Professor Hassan K. Khalil's 60th birthday). [http://dcdis001.watam.org/volumes/contents2010/v17n6b.html; number of citations: **6**].

[J13] U. Mettin, P. La Hera, A.S. Shiriaev, and, L.B. Freidovich, “Parallel elastic actuators as a control tool for preplanned trajectories of underactuated mechanical systems,” *The International Journal of Robotics Research*, vol. 29, no. 9, pp. 1186–1198, 2010. [http://dx.doi.org/10.1177/0278364909344002; number of citations: **15**].

[J14] **(*)** A.S. Shiriaev, L.B. Freidovich, and S.V. Gusev, “Transverse linearization for controlled mechanical systems with several passive degrees of freedom,” *IEEE Transactions on Automatic Control*, vol. 55, no. 4, pp. 893–906, 2010. [http://dx.doi.org/10.1109/TAC.2010.2042000; number of citations: **46**].

[J15] L.B. Freidovich, A. Robertsson, A.S. Shiriaev, and R. Johansson, “LuGre-model-based friction compensation,” *IEEE Transactions on Control Systems Technology*, vol. 18, no. 1, pp. 194–200, 2010. [http://dx.doi.org/10.1109/TCST.2008.2010501; number of citations: **75**].

[J16] A.S. Shiriaev and L.B. Freidovich, "Transverse linearization for impulsive mechanical systems with one passive link," *IEEE Transactions on Automatic Control*, vol. 54, no.12, pp. 2882–2888, 2009. [http://dx.doi.org/10.1109/TAC.2009.2033760; number of citations: **18**].

[J17] P. La Hera, L.B. Freidovich, A.S. Shiriaev, and U. Mettin, "New approach for swinging up the Furuta pendulum: Theory and experiments," *Mechatronics*, vol. 19, no. 8, pp. 1240–1250, 2009. [http://dx.doi.org/10.1016/j.mechatronics.2009.07.005; number of citations: **17**].

[J18] **(*)** L.B. Freidovich, U. Mettin, A.S. Shiriaev, and M.W. Spong, "A passive 2-DOF walker: Hunting for gaits using virtual holonomic constraints," *IEEE Transactions on Robotics*, vol. 25, no. 5, pp. 1202–1208, 2009. [http://dx.doi.org/10.1109/TRO.2009.2028757; number of citations: **26**].

[J19] L.B. Freidovich, A.S. Shiriaev, F. Gómez-Estern, F. Gordillo, and J. Aracil, "Modification via averaging of partial-energy-shaping control for orbital stabilization: cart-pendulum example," *International Journal of Control*, vol. 82, no. 9, pp. 1582–1590, 2009. [http://dx.doi.org/10.1080/00207170802596272; number of citations: **6**].

[J20] L.B. Freidovich, P. La Hera, U. Mettin, A. Robertsson, A.S. Shiriaev, and R. Johansson, "Shaping stable periodic motions of inertia wheel pendulum: theory and experiment," *Asian Journal of Control*, vol. 11, no. 5, pp. 548–556, 2009. [http://dx.doi.org/10.1002/asjc.135; number of citations: **6**].

[J21] L.B. Freidovich, A.S. Shiriaev, F. Gordillo, F. Gómez-Estern, and J. Aracil, "Partial-energy-shaping control for orbital stabilization of high frequency oscillations of the Furuta pendulum," *IEEE Transactions on Control Systems Technology*, vol. 17, no. 4, pp. 853–858, 2009. [http://dx.doi.org/10.1109/TCST.2008.2005734; number of citations: 0].

[J22] L.B. Freidovich and H.K. Khalil, "Performance recovery of feedback-linearization-based designs," *IEEE Transactions on Automatic Control*, vol. 53, no. 10, pp. 2324–2334, 2008. [http://dx.doi.org/10.1109/TAC.2008.2006821; number of citations: **97**].

[J23] A.S. Shiriaev, L.B. Freidovich, and I.R. Manchester, "Can we make a robot ballerina perform a pirouette? Orbital stabilization of periodic motions of underactuated mechanical systems," *Annual Reviews in Control*, vol. 32, no. 2, pp. 200–211, 2008. [http://dx.doi.org/10.1016/j.arcontrol.2008.07.001; number of citations: **36**].

[J24] U. Mettin, P. La Hera, L.B. Freidovich, and A.S. Shiriaev, "Motion planning for humanoid robots based on the virtual constraints extracted from recorded human movements," *Intelligent Service Robotics*, vol. 1, no. 4, pp. 289–301, 2008. [http://dx.doi.org/10.1007/s11370-008-0027-2; number of citations: **1**].

[J25] L.B. Freidovich, A. Robertsson, A.S. Shiriaev, and R. Johansson, "Periodic motions of the Pendubot via virtual holonomic constraints: Theory and experiments," *Automatica*, vol. 44, no. 3, pp. 785–791, 2008. [http://dx.doi.org/10.1016/j.automatica.2007.07.011; number of citations: **45**].

## 2. Peer-reviewed conference papers[1] (2008-2015)

[C1] A. Shiriaev, L. Freidovich, A. Robertsson, A. Andersson, and R. Johansson, "IQC arguments for analysis of the 3-state Moore-Greitzer compressor system," to appear in Proc. of the *1st IFAC Conference on Modelling, Identification and Control of Nonlinear Systems*, June 24-26, 2015, Saint-Petersburg, Russia.

[C2] M. Surov, A. Shiriaev, L. Freidovich, S. Gusev, and L. Paramonov, "Case study in non-prehensile manipulation: planning and orbital stabilization of one-directional rollings for the Butterfly robot," to appear in Proc. of the *IEEE International Conference on Robotics and Automation*, May 26-30, 2015, Seattle, Washington, USA.

[C3] C. Vazquez, S. Aranovskiy, L. Freidovich, and L. Fridman, "Second Order Sliding Mode Control of an Industrial Hydraulic System" to appear in Proc. of the *53rd IEEE Conference on Decision and Control*, December 15-17, 2014, Los Angeles, California, USA, pp. 5630–5635. [Number of citations: **0**].

[C4] C. Vazquez, S. Aranovskiy, and L. Freidovich, "Sliding mode control of a forestry-standard mobile hydraulic system" in Proc. of the *13th Variable Structure Systems Workshop*, June 29-July 2, 2014, Nantes, France, 6p. [Number of citations: **2**].

[C5] C. Vazquez, S. Aranovskiy, and L. Freidovich, "Time-varying gain second order sliding mode differentiator," in Proc. of the *19th World Congress of the International Federation of Automatic Control*, August 24-29, 2014, Cape Town, South Africa, pp. 1374–1379. [Number of citations: **2**].

[C6] S. Fodor and L. Freidovich, "Static friction modeling and identification for standard mechatronic systems", in Proc. of the *14th Mechatronics Forum International Conference*, June 16-18, 2014, Karlstad, Sweden, pp. 30–36. [Number of citations: **0**].

[C7] I Yung, S. Aranovskiy, and L. Freidovich, "Case Study on Non-Ideal Current Tracking in Amplifiers for Voltage-Driven Manipulators", in Proc. of the *14th Mechatronics Forum International Conference*, June 16-18, 2014, Karlstad, Sweden, pp. 126–131. [Number of citations: **0**].

[C8] A.A. Rubanova, A. Robertsson, A. Shiriaev, L. Freidovich, and R. Johansson, "Robustness of the Moore-Greitzer compressor model's surge subsystem with new dynamic output feedback controllers," in Prep. of the *19th World Congress of The International Federation of Automatic Control*, Cape Town, South Africa. August 24-29, 2014, pp. 3690–3695. [Number of citations: **0**].

[C9] A.S. Shiriaev, L.B. Freidovich, and M.W. Spong, "Controlled Invariants and Trajectory Planning for Underactuated Mechanical Systems," in Proc. of the *52nd IEEE Conference on Decision and Control*, December 10-13, 2013, Firenze, Italy, pp. 1628–1633. [Number of citations: **0**].

[C10] **(*)** S. Pchelkin, A.S. Shiriaev, A. Robertsson, and L.B. Freidovich, "Integrated Time-Optimal Trajectory Planning and Control Design for Industrial Robot Manipulator," in Proc. of the *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, November 3-8, 2013, Tokyo, Japan, pp. 2521–2526. [Number of citations: **2**].

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[1] Extended and modified versions of some of the listed conference contributions are published in peer-reviewed journals. The changes, however, are often significant making these publications complimentary.

[C11] L.T. Aguilar, L. Freidovich, Yu. Orlov, and J.O. Mérida "Performance analysis of relay feedback position regulators for manipulators with Coulomb friction," to appear in Proc. of *European Control Conference*, July 17-19, 2013, Zurich, Switzerland. [Number of citations: **0**].

[C12] A.A. Rubanova, A. Robertsson, A. Shiriaev, L. Freidovich, and R. Johansson, "Analytic Parameterization of Stabilizing Controllers for the Surge Subsystem of the Moore-Greitzer Compressor Model," in Proc. of *American Control Conference*, June 17-19, 2013, Washington, DC, USA, pp. 5257–5262. [Number of citations: **0**].

[C13] A.S. Shiriaev, L.B. Freidovich, and M.W. Spong, "A remark on controlled Lagrangian approach for completely integrable mechanical systems," in Proc. of the *4th IFAC Workshop on Lagrangian and Hamiltonian Methods for Non Linear Control*, August 29-31, 2012, Bertinoro, Italy, vol. 4, part 1, pp. 54–59. [Number of citations: **0**].

[C14] L. Freidovich, F. Gordillo, A. Shiriaev, and F. Gomez-Estern, "On generating pre-defined periodic motions in underactuated mechanical systems: the cart-pendulum example," in Proc. of the *IFAC World Congress*, Milano, August 28 – September 2, 2011, pp. 4588–4593. [Number of citations: **0**].

[C15] M. Meza-Sánchez, L.T. Aguilar, A. Shiriaev, L. Freidovich, and Yu. Orlov, "Nonlinear Output Feedback H-infinity-Tracking Control of a 3-DOF Underactuated Helicopter," in Proc. of the *IFAC World Congress*, Milano, August 28 – September 2, 2011, pp. 11145-11150. [Number of citations: **1**].

[C16] S.S. Pchelkin, A.S. Shiriaev, U. Mettin, L.B. Freidovich, T. Aoyama, Z. Lu, and T. Fukuda, "Shaping energetically efficient brachiation motion for a 24-DOF gorilla robot," in Proc. of *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),* September 25-30, 2011, pp.5094–5099. [Number of citations: **2**].

[C17] D. Ortíz Morales, S. Westerberg, P. La Hera, U. Mettin, L. Freidovich, and A. Shiriaev, "Open-loop control experiments on driver assistance for crane forestry machines," in Proc. of the *International Conference on Robotics and Automation*, Shanghai, China, May 9-13, 2011, pp.1797-1802. [Number of citations: **3**].

[C18] S. Pchelkin, A. Shiriaev, L. Freidovich, U. Mettin, and W. Kwon, "Natural sit-down and chair-rise motions for a humanoid robot," in Proc. of the *49th IEEE Conference on Decision and Control*, December 15-17, 2010, Atlanta, GA, USA, pp. 1136-1141. [Number of citations: **7**].

[C19] D. Ortíz Morales, P. La Hera, U. Mettin, L. Freidovich, A. Shiriaev, S. Westerberg, "Steps in Trajectory Planning and Controller Design for a Hydraulically Driven Crane with Limited Sensing," in Proc. of the *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*, October 18-22, 2010, Taipei, Taiwan, pp. 3836-3841. [Number of citations: **2**].

[C20] P.X. La Hera, L. Freidovich, A. Shiriaev, and U. Mettin, "Traversing from point-to-point along a straight line with a ballbot," in Proc. of the *8th IFAC Symposium on Nonlinear Control Systems*, September 1-3, 2010, Bologna, Italy. [Number of citations: 0].

[C21] L. Freidovich and A. Shiriaev, "Transverse linearization for an underactuated compass-like biped robot and analysis of the closed-loop system," in Proc. of the *8th*

*IFAC Symposium on Nonlinear Control Systems*, September 1-3, 2010, Bologna, Italy. [Number of citations: **4**].

[C22] P.X. La Hera, A. Shiriaev, L. Freidovich, and U. Mettin, “Gait Synthesis for a Three-Link Planar Biped Walker with One Actuator,” in Proc. of the *IEEE International Conference on Robotics and Automation*, May 3-8, 2010, Anchorage, Alaska, USA, pp. 1715–1720. [Number of citations: **2**].

[C23] U. Mettin, A. Shiriaev, L. Freidovich, and M. Sampei, “Optimal Ball Pitching with an Underactuated Model of a Human Arm,” in Proc. of the *IEEE International Conference on Robotics and Automation*, May 3-8, 2010, Anchorage, Alaska, USA, pp. 5009–5014. [Number of citations: **12**].

[C24] L.B. Freidovich, and A. Shiriaev, “Transverse linearization for mechanical systems with passive links, impulse effects, and friction forces,” in Proc. of the *48th IEEE Conference on Decision and Control*, December 16-18, 2009, Shanghai, China, pp. 6490–6495; the presentation was nominated (selected into the final list of 5 candidates) for *Guan Zhao-Zhi Award*. [Number of citations: **5**].

[C25] U. Mettin, P.X. La Hera, D.O. Morales, A.S. Shiriaev, L.B. Freidovich, and S. Westerberg, “Trajectory planning and time-independent motion control for a kinematically redundant hydraulic manipulator,’’ in Proc. of the *14th International Conference on Advanced Robotics*, June 22-26, 2009, Munich, Germany, pp. 1–6. [Number of citations: **5**].

[C26] S. Westerberg, U. Mettin, A.S. Shiriaev, L.B. Freidovich, and Y. Orlov, “Motion planning and control of a simplified helicopter model based on virtual holonomic constraints,’’ in Proc. of the *14th International Conference on Advanced Robotics*, June 22-26, 2009, Munich, Germany, pp. 1–6. [Number of citations: **7**].

[C27] A.S. Shiriaev, R. Johansson, A. Robertsson, and L.B. Freidovich, “Criteria for global stability of coupled systems with application to robust output feedback design for active surge control,” in Proc. of the *IEEE Multi-conference on Systems and Control*, July 8-10, 2009, St. Petersburg, Russia, pp. 1021–1026. [Number of citations: **2**].

[C28] L.T. Aguilar, I. Boiko, L. Fridman, and L. Freidovich, “Inducing oscillations in an inertia wheel pendulum via two-relays controller: Theory and experiments,” in Proc. of the *American Control Conference*, June 10-12, 2009, St. Louis, Missouri, USA, pp. 65–70. [Number of citations: **9**].

[C29] A.S. Shiriaev, L.B. Freidovich, and S.V. Gusev, “Transverse linearization for mechanical systems with several passive degrees of freedom with applications to orbital stabilization,” in Proc. of the *American Control Conference*, June 10-12, 2009, St. Louis, Missouri, USA, pp. 3039–3044. [Number of citations: 0].

[C30] P. La Hera, A. Shiriaev, L.B. Freidovich, and U. Mettin, “Orbital stabilization of a pre-planned periodic motion to swing up the Furuta Pendulum: Theory and experiments,” in Proc. of the *IEEE International Conference on Robotics and Automation*, May 12-17, 2009, Kobe, Japan, pp. 3562–3567. [Number of citations: **4**].

[C31] U. Mettin, P. La Hera, L.B. Freidovich, and A. Shiriaev, “How springs can help to stabilize motions of underactuated systems with weak actuators,” in Proc. of the *47th*

*IEEE Conference on Decision and Control*, December 9-11, 2008, Cancun, Mexico, pp. 5963–5968. [Number of citations: **2**].

[C32] A. Shiriaev, L.B. Freidovich, and I. Manchester, "Periodic motion planning and analytical computation of transverse linearizations for hybrid mechanical systems," in Proc. of the *47th IEEE Conference on Decision and Control*, December 9-11, 2008, Cancun, Mexico, pp. 4326–4331. [Number of citations: **5**].

[C33] L.B. Freidovich, U. Mettin, A. Shiriaev, and M.W. Spong, "A passive 2DOF walker: Finding gait cycles using virtual holonomic constraints," in Proc. of the *47th IEEE Conference on Decision and Control*, December 9-11, 2008, Cancun, Mexico, pp. 5214–5219. [Number of citations: **2**].

[C34] L.B. Freidovich, A.S. Shiriaev, and I.R. Manchester, "Stability analysis and control design for an underactuated walking robot via computation of a transverse linearization," in Proc. of the *17th IFAC World Congress*, July 6-11, 2008, Seoul, Korea, pp. 10166–10171. [Number of citations: **16**].

[C35] A.S. Shiriaev, R. Johansson, A. Robertsson, and L.B. Freidovich, "Separation principle for a class of nonlinear systems augmented with observers," in Proc. of the *17th IFAC World Congress*, July 6-11, 2008, Seoul, Korea, pp.6196–6201. [Number of citations: **4**].

## 3. Monographs - none

## 4. Research review articles - none

## 5. Books and book chapters (2008-2015)

[B1] L.B. Freidovich, *Control Methods for Robotic Applications. Lecture notes*, 213 pages, National Research University of Information Technologies, Mechanics, and Optics (NRU ITMO), St. Petersburg, Russia, 2013. [http://libris.kb.se/bib/14765489; number of citations: **0**].

[B2] L.B. Freidovich, *Optimal Control for Linear Systems. Lecture notes*, 130 pages, National Research University of Information Technologies, Mechanics, and Optics (NRU ITMO), St. Petersburg, Russia, 2013. [http://libris.kb.se/bib/14765422; number of citations: **1**].

[B3] L.B. Freidovich and A.S. Shiriaev, "Transverse linearization for underactuated nonholonomic mechanical systems with application to orbital stabilization," in *Lecture Notes in Control and Information Sciences* (LCCC Theme Semester), Vol. 417, Distributed Decision Making and Control, R. Johansson and A. Rantzer eds., 2012, Chapter 11, pp. 243–256, Springer, ISBN 978-1-4471-2264-7. [http://dx.doi.org/10.1007/978-1-4471-2265-4_11; number of citations: 0].

## 6. Patents - none

## 7. Open-access computer programs or databases - none

## 7. Popular science articles/presentations (2008-2015)

[P1] “Docent lecture” at TFE, Umeå University, “Control theory: history, state of the art, and challenges,” September 2010.

## Scientific outcome (1996-2015)

- **35** peer-reviewed journal articles; **58** peer-reviewed international conference contributions; **2** books (lecture notes), and **2** book chapters.
- Google scholar page with complete citation statistics: http://scholar.google.com/citations?user=VBekdAUAAAAJ

## The five most cited publications (*1996-2015, according to* ***Google Scholar*** *but without counting self-citations*)

- L.B. Freidovich and H.K. Khalil, “Performance recovery of feedback-linearization-based designs,” *IEEE Transactions on Automatic Control*, vol. 53, no. 10, pp. 2324–2334, 2008. [Number of citations: **97**].
- L.B. Freidovich, A. Robertsson, A.S. Shiriaev, and R. Johansson, “LuGre-model-based friction compensation,” *IEEE Transactions on Control Systems Technology*, vol. 18, no. 1, pp. 194–200, 2010. [Number of citations: **75**].
- A.S. Shiriaev, L.B. Freidovich, and S.V. Gusev, “Transverse linearization for controlled mechanical systems with several passive degrees of freedom,” *IEEE Transactions on Automatic Control*, vol. 55, no. 4, pp. 893–906, 2010. [Number of citations: **46**].
- L.B. Freidovich, A. Robertsson, A.S. Shiriaev, and R. Johansson, “Periodic motions of the Pendubot via virtual holonomic constraints: Theory and experiments,” *Automatica*, vol. 44, no. 3, pp. 785–791, 2008. [Number of citations: **45**].
- L.B. Freidovich and H.K. Khalil, “Lyapunov-based switching control of nonlinear systems using high-gain observers,” *Automatica*, vol. 43, no. 1, pp. 150–157, 2007. [http://dx.doi.org/10.1016/j.automatica.2006.08.010; number of citations: **45**].

## CV

**Name:**Leonid Freidovich
**Birthdate:** 19730704
**Gender:** Male
**Doctorial degree:** 1999-06-16
**Academic title:** Docent
**Employer:** Umeå universitet

## Research education

**Dissertation title (swe)**

Logic-Based Switching Control of Nonlinear Systems Using High-Gain Observers

**Dissertation title (en)**

Logic-Based Switching Control of Nonlinear Systems Using High-Gain Observers

| | | |
|---|---|---|
| **Organisation** | **Unit** | **Supervisor** |
| Michigan State University, USA<br>Not Sweden - Higher Education institutes | Department of Mathematics | Hassan K. Khalil |
| **Subject doctors degree** | **ISSN/ISBN-number** | **Date doctoral exam** |
| 10199. Annan matematik | | 2005-05-06 |

**Dissertation title (swe)**

Stability and Control of Robotic Manipulators

**Dissertation title (en)**

Stability and Control of Robotic Manipulators

| | | |
|---|---|---|
| **Organisation** | **Unit** | **Supervisor** |
| Saint Petersburg State Polytechnical University, Russia<br>Not Sweden - Higher Education institutes | Department of Mechanics and Control Processes | Anatoli A. Pervozvanski |
| **Subject doctors degree** | **ISSN/ISBN-number** | **Date doctoral exam** |
| 20202. Reglerteknik | | 1999-06-16 |

## Publications

| | |
|---|---|
| **Name:**Leonid Freidovich | **Doctorial degree:** 1999-06-16 |
| **Birthdate:** 19730704 | **Academic title:** Docent |
| **Gender:** Male | **Employer:** Umeå universitet |

Freidovich, Leonid has not added any publications to the application.

## Register

### Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

*Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.*

*Applications with an organisation as applicant is automatically signed when the application is registered.*