# *Application*

2015-03-31

| 2015-04315 | Smith, Christian | NT-2 |
|---|---|---|

### Information about applicant

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**Project site:** CVAP, Datorseende och robotik

### Information about application

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

**Type of grant:** Projektbidrag

**Focus:** Unga forskare

**Subject area:**

**Project title (english):** Unifying Control and Perception for Efficient Human-Robot Hand-Overs

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

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

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

**Classification code:** 10207. Datorseende och robotik (autonoma system), 20201. Robotteknik och automation

**Keywords:** Human-Robot Interaction, Motion Modelling, Domestic Robotics, perception, control

### Funds applied for

| **Year:** | 2016 | 2017 | 2018 | 2019 |
|---|---|---|---|---|
| **Amount:** | 1,264,000 | 1,319,000 | 1,424,000 | 1,539,000 |

**Descriptive data**

## Project info

### Project title (Swedish)*

Delade modeller för perception och styrning för effektiv människa-robotinteraktion

### Project title (English)*

Unifying Control and Perception for Efficient Human-Robot Hand-Overs

### Abstract (English)*

In this project, we study human-robot interaction, focusing on scenarios where objects are handed from one of the actors to the other. We will study representations of object handing actions, with the aim to find models that will enable robots to interact more efficiently with humans. The developed models should make it possible to describe human and robot motion in the same framework, supporting real-time estimation and prediction of human motions and intentions, and to generate robot motions that are predictable and legible to the human.

The project will carry over four years. The initial year will be focused on structured data gathering, formalization of performance metrics for evaluation, and setup of experimental robotic system. The following years will focus on model development, to determine what parametrizations best fit the observed data, as well as developing methods to automatically extract, estimate and predict parameters from observations, with the target to find solutions that are applicable in real-time. The final year will focus on evaluation of the models and methods, with implementation and experiments on a real system. There will be several shorter iterations of the overall process, as experimental results give insights into model development and vice versa.

The initial candidate framework for modelling the object handover actions is Dynamic Movement Primitives, a set of differential equations that are stable, robust to disturbances, and can be made to fit observed human motions arbitrarily well. By adding assumptions on the the human movements, based on automated learning from recorded data using statistical methods from machine learning, we expect to be able to fill in the part of a movement that has not yet been observed. This will allow real-time analysis of motions, and enable predictions of motion targets and intended action outcomes. The project will employ a PhD student full time for the duration of the project, as well as include active participation of the PIs.

The expected impact of the project is twofold. The first is to generate a better understanding of the object handing actions, and the appropriate models to describe it. The second is that this should result in more efficient human-robot handovers, for the benefit of human-robot collaborative systems in diverse fields such as manufacturing, service, and assistive robotics.

### Popular scientific description (Swedish)*

Det har länge varit ovanligt att hitta robotar i någon större mängd utanför den tunga industrin, men på senare år har man börjat införa dem i ett ökande antal nya tillämpningar i samhället. Vi ser robotdammsugare, självparkerande bilar och andra autonoma system. Inom sjukvården genomförs vissa operationer med hjälp av kirurgirobotar.

Vi tänker oss att denna utveckling är en accelererande trend, men det finns ännu många arbeten inom såväl den lättare tillverkningsindustrin som inom serviceyrken som kräver mäsnkligt handlag. För att kunna effektivisera dessa, och avlasta mänskliga arbetare de tyngsta eller mest repetitiva och tråkiga arbetsuppgifterna, krävs troligtvis att vi inför robotar som kan samarbeta direkt med människor, i mänskliga miljöer, och dela uppgifterna efter lämplighet och förmåga.

En viktig förmåga för robotar som ska samarbeta med människor, är att kunna överlämna eller ta emot olika föremål, som t.ex verktyg och arbetsstycken, eller hushållsaker som en hjälpbehövande människa inte kan eller vill hämta själv. Trots stora framsteg inom olika grenar av robottekniken, är detta fortfarande ett svårt problem. Vi människor kan utan ansträngning överlämna eller ta emot olika föremål från varandra utan att behöva förhandla och komma överens om när, var och hur överlämningen skall ske. Vi räcker helt enkelt över föremålet till mottagaren som ser detta, och tar emot det.

Syftet med forskningsprojektet är att utveckla denna förmåga för robotar. Vi vill att det ska vara lika enkelt och naturligt att överlämna föremål av olika storlek och typ mellan en robot och en människa som mellan två människor. För att uppnå detta behöver vi utveckla modeller för hur vi människor rör oss när vi överlämnar föremål, och hur man genom att observera denna rörelse kan förstå motpartens avsikter. Dessa modeller kan sedan användas både till att hjälpa roboten att förutse var, när och hur en människa ämnar överlämna ett föremål, och till att låta roboten överlämna föremål på sätt som gör det så naturligt och lätt som möjligt för en samarbeteande människa att förstå hur man ska ta emot föremålet.

## Project period

### Number of project years*

4

### Calculated project time*

2016-01-01 - 2019-12-31

## Deductible time

### Deductible time

| | Cause | Months |
|---|---|---|
| **1** | Parental leave | 4 |
| | Total | 4 |

Career age: 59

Career age is a description of the time from your first doctoral degree until the last day of the call. Your career age change if you have deductible time. Your career age is shown in months. For some calls there are restrictions in the career age.

## 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*** | 1. Naturvetenskap > 102. Data- och informationsvetenskap (Datateknik) > 10207. Datorseende och robotik (autonoma system)<br>2. Teknik > 202. Elektroteknik och elektronik > 20201. Robotteknik och automation |

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

**Keyword 1***

Human-Robot Interaction

**Keyword 2***

Motion Modelling

**Keyword 3***

Domestic Robotics

**Keyword 4**

perception

**Keyword 5**

control

## 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*

Inga etiska ställningstaganden är aktuella för detta projekt

### The project includes handling of personal data

No

### The project includes animal experiments

No

### Account of experiments on humans

No

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## Research plan

# Unifying Control and Perception for Human-Robot Hand-Overs

## 1 Purpose and Aims

In the near future, we expect robots that provide advanced service in close collaboration with humans to become an integral part of society, in both industrial and domestic settings, or as assistants in home care. These future robotic assistants and co-workers are expected to function autonomously along humans in human-centric environments, filling roles that only humans can fill today. They must therefore be able to perform smooth, swift, robust, and safe interaction with humans. In all application domains, one of the key components for cooperating with humans is the capability to give and receive objects. In industry, this may include handing over tools or workpieces, a public service robot may deliver goods or collect objects no longer needed, while a domestic service robot may fetch different objects for a disabled inhabitant[1].

As is detailed in Section 2, the efficiency of object handovers is highly influenced by small variations in trajectory, timing, and placement of robot movements. Motions that are similar to human behavior result in better performance, and it is also reasonable to exploit the fact that most humans have already internalized the communication protocols inherent in human-human interaction and body-language, as this should leviate the need for specialist training and result in faster implementation for non-specialist users. However, currently existing human-robot systems either assume that the handover task is predefined in terms of any or all of timimg, location, and interaction forces, have performance that is significantly slower than what a human could perform, or is completetly passive and just follows the human's lead. A basic research question that remains to solve is thus how to formalize object hand-over tasks so that the robot can take an equally active part in the collaboration as a human could, performing as swiftly and robustly.

**The main objective of this project is to study control and perception for human-robot handovers, grounded in current understanding of human task execution, to gain a better understanding of suitable representations and models**, with the goal of enabling robots to be active and efficient partners to humans for object handing tasks. To achieve this, we will develop and evaluate the theoretic foundations in realistic scenarios with human-robot hand-over tasks, demonstrating the feasibility and utility of the approach. As modeling tools, we will use techniques from automatic control, machine learning, and stochastic estimation, and contributions beyond the state-of-the art will be made regarding several of the system components, for the benefit of several related fields of study. We especially expect that the project will contribute with models and methods for human motion tracking, algorithms for parameter fitting and learning, as well as control and perception techniques for robots in general.

### 1.1 Basic idea and scientific challenges

Observing the different steps involved when we as humans hand different objects to one another, we see several important substeps, all of which will have to be modelled and replicated to an equivalent level by a robot system that we want to achiece comparable performance:

- **Object giving:** Handing an object to another person. Presenting the object to another includes moving it in such a way that we communicate not only our intent to give the object, but also dynamic properties of the object and the handover. For example, our way of holding and moving the object will convey information about object mass, and appropriate ways to handle it.

- **Object receiving:** Reaching to receive an object given to us by another. As humans we are able

[1] Y.S. Choi, T. Deyle, T. Chen, J.D. Glass, C. Kemp, "A list of household objects for robotic retrieval prioritized by people with ALS", IEEE International Conference on Rehabilitation Robotics, 2009, pp. 510–517.

to anticipate the location and timing of an intented handover without explicitely communicating this information, and can perform swift and robust handovers. By observing the motion of the receiver, the giver can understand if the receiver is ready to accept the object at the time and position intended by the giver.

- **Transfer of control:** In an handover, an object initially held by only the giver is temporarily held by both parties. When the control of the jointly held object is transferred to the receiver, the details of this action can also be understood by the partner through implicit communication, without the need of explicite communication. Most of the time, control transfer can be performed quickly without dropping objects.

All the above subtasks are very natural and intuitive to humans but are still difficult to demonstrate with current robot technology[2]. As humans give objects to one another, visual observation of the other conveys information that — possibly via the mirror neuron system[3] — helps us understand enough of the others intentions to be able to match the motion in real time. To implement similarly smooth object handing for a robot replacing one of the humans, the robot will need an appropriate representation of the motor actions involved to be able to anticipate the humans actions[4]. As **the first scientific challenge**, we will address the problem of formulating a common representation to model the different motions involved in hand-over tasks, such as presenting an object to the receiver, or reaching out to receive a presented object. This representation should be applicable to to describe and synthesize both human and robot motion, and allow for encoding the dynamic properties that the handled object imparts on the motion, as well as the task-related intentions of the action.

Object handing interaction is a dynamic and inherently real-time task. It is not enough to be able to accurately describe the actions involved, but this information has to be processed online. Robot sensors may not be able to extract all information from human motion, and as the robot system will have limited dynamics (not least for safety reasons), motions may have to be planned or initiated well in advance. For these reasons, it is important that knowledge of human motion can be extracted and estimated from limited sensor data, and predicted to estimate the intended target positions of different motions. As **the second scientific challenge**, we will address the problem of estimating and predicting human motions and intentions based on the representations developed, as well as study how this knowledge can best be exploited by a robot to enhance interactive performance.

There is also a **technical challenge** in the implementation and evaluation of the model-based action estimation and handover actions on a physical robotic system. This icludes incorporating sensor readings, data processing, and motion control of the robot manipulator used. This will initially be carried out on setups available in the lab, see Fig. 1, but should contain general enough solutions to enable implementation on generic setups as well.

**The main objectives** of this project is hence the development of the theory and models necessary to realize advanced interactive robot systems based on multisensory feedback that are capable of smooth hand-overs, either giving or receiving objects to/from humans. The main tools to be used to achive these objectives will be

i) Statistical learning to find the most apropriate parametric representations of handover actions,

ii) Adaptive control and estimation techniques, to identify, predict, and act on the intended motion of a human partner,

[2]S. Glasauer, M. Huber, P. Basili, A. Knoll, and T. Brandt, "Interacting in time and space: Investigating human-human and human-robot joint action", Ro-Man, 2010, pp. 252–257

[3]F Filimon, JD Nelson, DJ Hagler, MI Sereno, "Human cortical representations for reaching: mirror neurons for execution, observation, and imagery", Neuroimage 37, no. 4, 2007, 1315–1328.

[4]K. Strabala, M-K Lee, A. Dragan, J. L. Forlizzi, S. Srinivasa, M. Cakmak, and V. Micelli, "Towards Seemless Human–Robot Handovers", Journal of Human-Robot Interaction, vol.2, no. 1, 2013, pp.112–132.

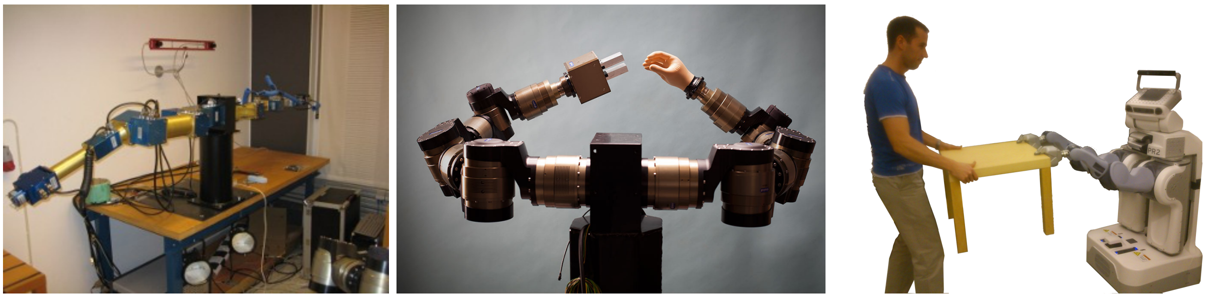

Figure 1: *Robots at CAS, from left: 2×6 DoF arms, mobile dual 7 DoF arm robot, and PR2 robot*

iii) Sensors and systems integration to enable and evaluate the above.

# 2 Survey of the Field

This project will build on previous results from two distinct fields — the study of modelling human motion, and human-robot interaction (HRI). The most relevant studies from these fields are summarized below.

## 2.1 Human motion modelling

Current state of the art in human-robot handovers is mainly based on the following phenomenological observations of human-human handovers: Human receivers reach the transfer point almost simultaneously with the giver, exibiting bell-shaped velocity profiles[5,6]. The approaching motion of a human walking up to another human to hand over an object shows that the giver signals the intention in advance by initiating the giving motion before reaching the taker[7], which has also been verified to improve perceived object handing performance when implemented on a robot[8,9]

Measurements of the interaction forces during the joint grasping phase of a handover show that the giver ensures stability during handover, and that the reciever unloads the gravity forces from the giver before the giver releases and transfers control[10], and that human-robot handovers can be improved by letting the robot mimic this behavior[11].

A class of differential equations known as Dynamic movement primitives (DMP) have been shown to be a robust way to encode human and human-like motion for robots when learning to imitate

[5] S. Shibata, K. Tanaka, and A. Shimizu, "Experimental analysis of handing over," in Robot and Human Communication, 1995. RO-MAN'95 TOKYO, Proceedings., 4th IEEE International Workshop on, jul 1995, pp. 53–58.

[6] M. Huber, M. Rickert, A. Knoll, T. Brandt, and S. Glasauer, "Human-robot interaction in handing-over tasks," IEEE International Symposium on Robot and Human Interactive Communication, aug. 2008, pp. 107–112.

[7] P. Basili, M. Huber, T. Brandt, S. Hirche, and S. Glasauer, "Investigating human-human approach and hand-over," in Human Centered Robot Systems. Springer Berlin Heidelberg, 2009, vol. 6, pp. 151–160.

[8] Chao Shi, Masahiro Shiomi, Christian Smith, Takayuki Kanda, and Hiroshi Ishiguro, "A model of handing interaction towards a pedestrian", HRI2013 Video Session, Tokyo, Japan, March 06 2013.

[9] Chao Shi, Masahiro Shiomi, Christian Smith, Takayuki Kanda, and Hiroshi Ishiguro, "A model of distributional handing interaction for a mobile robot." Robotics Science and Systems, RSS2013, Berlin, Germany. 2013.

[10] W. P. Chan, C. A. C. Parker, H. F. M. V. der Loos, and E. A. Croft, "Grip forces and load forces in handovers: implications for designing human-robot handover controllers," in HRI, 2012, pp. 9–16.

[11] W. P. Chan, I. Kumagai, S. Nozawa, Y. Kakiuchi, K. Okada, M. Inaba, "Implementation of a Robot-Human Object Handover Controller on a Compliant Underactuated Hand Using Joint Position Error Measurements for Grip Force and Load Force Estimations", in IEEE International Conference on Robotics & Automation, 2014, pp 1190–1195

a human demonstration[12,13]. A DMP for the spatial trajectory $\mathbf{x}(t)$ can be formalized as:

$$\frac{1}{\tau}\ddot{\mathbf{x}} = \alpha(\beta(g-\mathbf{x})-\dot{\mathbf{x}})+\mathbf{g}_t^T\theta \tag{1}$$

Where $\tau$ is a time constant, $\alpha$ and $\beta$ are gains, $g$ is the goal position of the movement, and $\mathbf{g}_t^T\theta$ is a sum of weighted nonlinear basis functions (movement primitives) that force the trajectory into a specific shape. Being a superposition of a stable converging linear dynamical system and a linear combination of converging and stable primitive functions, DMP formulations result in stable and robust motion controllers that encode trajectories that can be made arbitrarily similar to demonstrated trajectories by increasing the number of primitive funtions. In practice, DMP have shown good performance for representing different motor actions for imitation, including the reaching motions for handovers [14], and should be a good candidate to use for the shared representations needed for a robot to generate human-lika handover actions.

For vision guided free reaching motion (such as the motion of handing an object or reaching to receive an object), a class of fifth-degree polynomial trajectories known as minimum jerk (MJ) have been shown to have good correspondance with the hand trajectory kinematics. MJ models have succesfully been applied to the task of estimating human reaching motion in realtime, both for one-dimensional motion[15], and three-dimensional reaching towards moving targets with an object in hand in a virtual environment[16]. MJ kinematic models have also been used for successful prediction of human hand motions when controlling a teleoperated robot[17,18].

***Progress beyond the state of the art:*** *We will develop a motion representation for handover motions, based on DMP. We will extend the state of the art by adding parametrisations that allow DMP trajectories to be fit to observed motions in real-time, as they are being executed, such that intended motion outcomes can be estimated and future motions be accurately predicted in real-time. Concretely, this entails estimation and prediction of the $\tau$, $g$, and $\mathbf{g}_t^T\theta$ terms of Equation (1). The same representations will also allow for generating similar motions on the robot, that can be understood in the same way by a human observer.*

## 2.2 Human-robot interaction

The action of handing an object from a robot to a human or vice-versa has been demonstrated on several different robot platforms, using different approaches based on theoretical insights or result-oriented heuristics. Demonstrated systems include those where the robot reaches out in the general vicinity of a human, closes the hand when an object is felt, and retracts the hand if grasping is

[12] Auke J. Ijspeert, Jun Nakanishi, and Stefan Schaal "Movement Imitation with Nonlinear Dynamical Systems in Humanoid Robots", In IEEE International Conference on Robotics and Automation 2002, pp 1398–1403.

[13] A. Ijspeert, J. Nakanishi, P. Pastor, H. Hoffmann, and S. Schaal, "Dynamical Movement Primitives: Learning Attractor Models forMotor Behaviors", Neural Computation, 25, pp.328–373.

[14] Miguel Prada, Anthony Remazeilles, Ansgar Koene and Satoshi Endo, "Dynamic Movement Primitives for Human-Robot interaction: comparison with human behavioral observation", IEEE/RSJ International Conference on Intelligent Robots and Systems, 2013, pp 1168–1175.

[15] B. Corteville, E. Aertbelien, H. Bruyninckx, and J. De Schutter, "Human-inspired robot assistant for fast point-to-point movements", IEEE International Conference on Robotics and Automation, 2007, pp 3639–3644.

[16] Christian Smith, Mattias Bratt, and Henrik I Christensen. "Teleoperation for a Ballcatching Task with Significant Dynamics", Neural Networks, Special Issue on Robotics and Neuroscience, vol 24, issue 4, pp. 604–620, May 2008.

[17] Christian Smith and Henrik I Christensen, "A Minimum Jerk Predictor for Teleoperation with Variable Time Delay" IEEE/RSJ International Conference on Intelligent Robots and Systems. pp 5621-5627, 2009.

[18] Christian Smith and Patric Jensfelt. "A Predictor for Operator Input for Time-Delayed Teleoperation" Mechatronics, special issue on Design Control Methodology, Vol 20:7, pp. 778-786, Oct 2010

deemed succesfull. The system lets the robot give objects to the human by merely dropping them, and having the human learn to take the object before the robot drops it[19]. Other work presents systems where a human takes an object from a robot, and the robot releases it when the human pulls hard enough on the object so the robot is no longer able to hold it in a stable grasp[20], or systems that plan trajectories to make the manipulated object easy to present to a human user[21]. Robot trajectories that are minimum-jerk like in cartesian space have been shown to give more efficient handing-over from robot to human than trapezoidal trajectories. Having the robot perform distinct motions that have a high contrast between holding an object and presenting it to a human have been shown to improve human understanding of robot intent, and improve handover performance[22]. Letting the robot generate motion plans that make the handover pose more accessible for the human has been shown to make handovers more fluent[23]. Studies have also shown that robots that proactively reach out to receive an object makes the transaction more fluent[24]. Faster and more fluent (but at approximately 7 seconds for the entire action, it is still very slow compared to human-human interaction) handovers result from robot adaptively matching humans motion when reaching to retreive object[25], while overall work performance has been shown to increase when a robot adapts its timing to the human co-worker[26]. It has also been shown that adding deliberate delays to the handover procedure causes a human to assume that the robot wants to communicate something other than just handing over the object [27]

While it is established that a successful and efficient procedure for handing an object to another agent requires several distinct steps that all ease the implicit communication of subgoals, a concrete formulation of an integrated system that can demonstrate this on a real robot is yet to be shown[28]. It has also been shown that human-robot collaboration can be made more efficient if effort is made to generate robot motions that are easy to understand by the human [29]

In summary, object handover is a well-known problem, but performance similar to human-human interaction has yet to be generally demonstrated in human-robot scenarios.

***Progress beyond the state of the art:*** *Our goal in the project is to use the shared representations of handover motions to develop methods for collaborative human-robot manipulation, enabling handover tasks of the same fluency and robustness as human-human interaction.*

[19] A. Edsinger and C. Kemp, "Human-robot interaction for cooperative manipulation: Handing objects to one another," IEEE International Symposium on Robot and Human interactive Communication, aug. 2007, pp. 1167–1172.

[20] K. Nagata, Y. Oosaki, M. Kakikura, and H. Tsukune, "Delivery by hand between human and robot based on fingertip force-torque information," in International Conference on Intelligent Robots and Systems, 1998, pp. 750–757

[21] J. Kim, J. Park, Y. Hwang, and M. Lee, "Advanced grasp planning for handover operation between human and robot," in 2nd International Conference on Autonomous Robots and Agents, 2004, pp. 13–15.

[22] M. Cakmak, S. Srinivasa, M. K. Lee, S. Kiesler, and J. Forlizzi, "Using spatial and temporal contrast for fluent robot-human hand-overs," in 6th ACM/IEEE International Conference on Human-Robot Interaction, February 2011.

[23] J. Mainprice, M. Gharbi, T. Simeon, and R. Alami, "Sharing effort in planning human-robot handover tasks," IEEE International Symposium on Robot and Human Interactive Communication, Paris, France, 2012.

[24] V. Micelli, K. Strabala, and S. Srinivasa, "Perception and control challenges for effective human-robot handoffs," in RSS Workshop: RGB-D - Advanced Reasoning with Depth Cameras, 2011.

[25] D. Lee, C. Ott, and Y. Nakamura, "Mimetic communication with impedance control for physical human-robot interaction," in Robotics and Automation, 2009. ICRA '09. IEEE International Conference on, may 2009, pp. 1535–1542.

[26] Markus Huber, Claus Lenz, Cornelia Wendt, Berthold Färber, Alois Knoll, Stefan Glasauer. "Increasing efficiency in robot-supported assemblies through predictive mechanisms: An experimental evaluation". IEEE RO-MAN: The 22nd IEEE International Symposium on Robot and Human Interactive Communication, 2013, pp 503–508

[27] H. Admoni, A. Dragan, S. Srinivasa, B. Scassellati. "Deliberate Delays During Robot-to-Human Handovers Improve Compliance With Gaze Communication". ACM/IEEE International Conference on Human-Robot Interaction, Bielfeld, Germany, 2014. pp 49–56.

[28] K. Strabala, M. K. Lee, A. Dragan, J. Forlizzi, S. Srinivasa, M. Cakmak, and V. Micelli, "Towards Seemless Human–Robot Handovers", Journal of Human-Robot Interaction, vol.2, no. 1, 2013, pp.112–132.

[29] A. Dragan, S. Bauman, J. Forlizzi, and S. Srinivasa. "Effects of Robot Motion on Human-Robot Collaboration". ACM/IEEE International Conference on Human-Robot Interaction, Portland Oregon, USA, 2015. pp 51–58.

# 3 Project Description

We will structure the research according to the objectives presented in Section 1. The planned work beyond the state of the art has already been mentioned and in the following section we outline three major milestones for the project.

We are primarilly interested in developing the basic theoretical framework for the outlined objectives. However, to prove the applicability of the proposed approaches, it is important that the developed theories and software components are evaluated both individually and at a system level. The workplan and milestones will be developed and evaluated around realistic task examples based on either a human handing objects of varying size and mass to a robot, or the robot handing objects of varying size and mass to the human.

We want to emphasize that these are only tentative example tasks and that the main aspect of experimental evaluation will be to study these or similar tasks that can be solved only by using a model that allows robust real-time estimation or prediction of the hand-over actions. The evaluation platform will be a human-sized robot with at least one articulated arm, starting out with existing robots at CAS, see Fig. 1. The aim is that the methods developed should be general, and independent of hardware platform, and be easily replicable on other setups. We will use and contribute to the open source software widely used in the robotics community.

Thus, this robotics project will progress in the common ground of three distinct research fields: control and estimation, computer science, and human-robot interaction, where the underlying unifying factor is the shared representation for human and robot actions, which is studied from these three different viewpoints.

## 3.1 Scientific Milestones

**Milestone 1: Initial Observations and Data Gathering (month 12)**

The first part of the project lies in problem formalization and constructing an initial data set. We will start with the formal definition of the handover scenarios, which also includes defining the workspace environment and choosing appropriate objects. Sensors for tracking human and object motion will also be set up, including external sensors such as cameras and motion capture, internal sensors such as force/torque and other load sensors of the robot, as well as more invasive sensors such as embedding accelrometers, force sensors, and similar in the interaction object. The initial scenario will have the robot and human in a partially shared workspace, with accessible locations where objects can be placed, see Figure 2.

The initial observations will include tracking of the object in the human's hand, and the robot will use a system mock-up to be able to reach and grasp the object, thus implementing a naïve approach to handovers, such as described in previous literature.

*Measure of success: A dataset for model development will be collected, along with a set of performance metrics. This first stage scenario will involve demonstration of simplified object handing, the performance of which will serve as a baseline of comparison for the models developed within the project.*

**Milestone 2: Model-Based Representation of Handover Actions (month 30).**

In the second stage of the project, which will start in parallell with the initial data gathering, we will work on model development, estimation, prediction, and synthesizing of handover movements. Dynamic Motion Primitives (DMP) will be used as the primary candidate for modelling, and adaptive estimation and probabalistic models such as gaussian processes may be used to fit parameters to model based on observations.

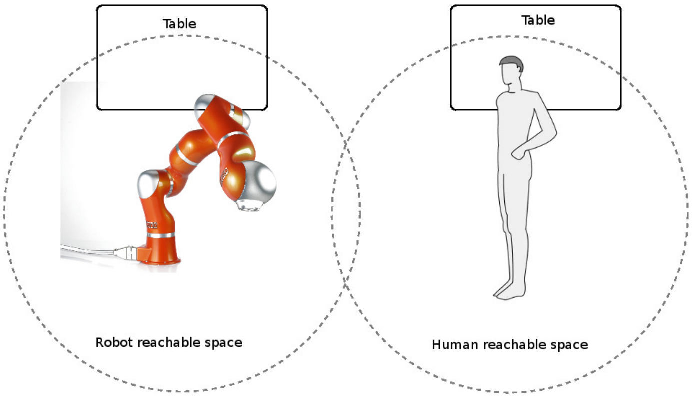


Figure 2: Sketch of the experimental setup. The robot and the human have a partially shared workspace for handovers, and separate storage locations (e.g. tables) for objects to hand over.

In this stage, the data gathered in the previous step will also be used to evaluate different sensors, starting with the richest possible set of sensors, enhancing object tracking by including data from embedded sensors such as accelerometers and cameras in the transferred object itself [30]. Models will then successively be developed to work with simpler sensors, such as an RGB camera with depth-sensing capabilities (e.g. Microsoft Kinect), and evaluated on the richer data gathered from more advanced or invasive sensors.

*Measure of success: The developed models show good agreement with actual observed motions, using a mimimum of free parameters. This allows efficient estimation and accurate prediction and generation of hand-over motions based on sensor readings.*

**Milestone 3: Efficient Handovers (month 48).**

Having developed a parametrical model for representing handover actions, and methods to observe, estimate, predict, and generate parameters for human-like actions, this is then implemented on an experimental setup that has the necessary hardware capabilities for human and object tracking and manipulation. This step will include not only the implementation of the system, but a significant amount of experimentation. The process will be cyclic, as improved performance of the handover functionality may potentially generate better and more realistic handover motion data. Thus, this step will potentially involve an iterative improvement of the models and the prediction system.

*Measure of success: In the final scenario, we will demonstrate fluent and efficient handovers, both from human to robot and from robot to human. The final evaluation will be experimental, where we show how the implemented system infers significant improvements on measurable quantities such as success rates, completion times, or learning curves for the users.*

# 4 Significance

This project aims at providing a break-through in understanding, modeling and integration of collaborative human-robot tasks for service or industrial environments. This requires concurrent research in areas of human-robot interaction, modelling, estimation, sensor based coordination, and control. The classical robotics systems have dealt with most of the problems during the last decade, but the approaches have been reductionistic such that each of the problems have been studied independently. We are aware of the current state-of-the-art and will not reinvent neither the problems nor the solutions.

[30] Christian Smith and Henrik I Christensen, “Wiimote Robot Control Using Human Motion Models”, IEEE International Conference on Intelligent Robots and Systems. pp 5509-5515, 2009

This project will allow for robotic handing of objects of different shapes and sizes in cooperation with people in complex, dynamic environments such as domestic, office, or workshop environments. The strategic importance for Sweden is clear given that no efficient cooperative arm systems for object handing have yet been demonstrated nationally.

The output from this project will a have large impact in the area of robotic systems at large. Such systems are today used both in medical and industrial settings and, even if a service robot scenario is considered, we will deal with basic theoretical issues and modeling which are common for all the above. Apart from the research and technological impact, we foresee a social impact as well. In future scenarios, users will not only use robots as tools but they will be assisted by agents with advanced cognitive and learning abilities, some of which are considered in this project. To conclude, it is our firm belief that the results will have a direct impact in different areas of robotics by enabling systems to assist and cooperate with humans in their everyday lives.

Given the fundamental nature of the proposed study, we expect that component findings from the project will feed into several related fields of study. We especially expect that the project will contribute with models and methods for human motion tracking, algorithms for parameter fitting and learning, as well as control and perception techniques for robots in general.

# 5 Preliminary Results

In previously published studies, we have shown that it is possible to accurately predict the target of human reaching motions in a teleoperation setting using minimum jerk models[31]. We have also demonstrated the effect of applying human motion models to robot locomotion to create more efficient handovers in public settings[32]. Furthermore, we have shown that adaptive estimation is an effective tool for robust estimation of the kinematics of physical human-robot interaction[33], as well as demonstrating a method for a robot to understand human intentions during non-verbal interaction[34].

In a yet unpublished prestudy, we have tested the applicability of DMP models to predicting human reaching motions during handovers by estimating the forcing terms of the dynamic system, and found that offline fitting to noise-free data is accurate for predictions, even if using only the first 20% of a measured motion, thus supporting the use of this model for representing human handover motions. As a proof of concept, we have also succesfully applied the results of minimum jerk based predictions for teleoperation for a small preliminary dataset of handover actions.

# 6 Employment

**Planned personnel:** We plan to employ a doctoral student with training in robotics, or estimation and control. The student will work along the outlined scientific problems. The PI also plans to invest a significant amount of reserach time on the project, and will supervise the student along with Prof.

[31] Christian Smith and Patric Jensfelt. "A Predictor for Operator Input for Time-Delayed Teleoperation" Mechatronics, special issue on Design Control Methodology, Vol 20:7, pp. 778-786, Oct 2010

[32] Chao Shi, Masahiro Shiomi, Christian Smith, Takayuki Kanda, and Hiroshi Ishiguro, "A model of distributional handing interaction for a mobile robot." Robotics Science and Systems, RSS2013, Berlin, Germany. 2013.

[33] Yiannis Karayiannidis, Christian Smith, Francisco Vina, and Danica Kragic. "Online Kinematics Estimation for Active Human-Robot Manipulation of Jointly Held Objects." IEEE/RSJ International Conference on Intelligent Robots and Systems, Tokyo, Japan. 2013, pp 4872-4878.

[34] Yiannis Karayiannidis, Christian Smith, and Danica Kragic. "Mapping Human Intentions to Robot Motions via Physical Interaction Through a Jointly-held Object." The 23rd IEEE International Symposium on Robot and Human Interactive Communication, Edinburgh, Scotland, UK, Aug 25-29, 2014.

Danica Kragic. There are several other ongoing projects in the fields of perception, control, and modelling for domestic robotics in the lab, and the student will benefit from the direct interaction with these.

# 7 Equipment

The research as planned here will mainly need two types of equipment. For the tracking and estimation of human motion, we initially plan to use different types of cameras, depth sensors, accelerometers, or magnetic pose trackers already available in the lab. For the human-robot object handing experiments, we will use one of the manipulators already available at CAS, see Figure 1, or those that the center is in the process of purchasing. Current manipulators include two custom-built, human-sized Schunk LWA arms with 7 degrees of freedom (DoF) each, a PR2 robot with two compliant 7 DoF arms, two human-sized custom built Schunk PowerCube arms with 6 DoF, one KUKA KR5 industrial manipulator with 6 DoF, and 5 NAO humanoid robots.

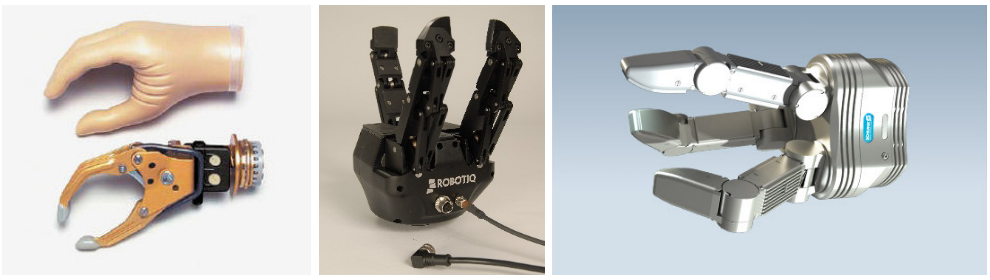


Figure 3: *Robotic hands available at the Centre for Autonomous Systems. From left to right: Otto Bock prosthetic hand, Robotiq three-fingered gripper, and Schunk dexterous three-fingered gripper.*

Object grasping will be done using either of the articulated hands available in the lab, both of which are equipped with tactile sensing capabilities, or a human-like Otto Bock prosthetic gripper, see Figure 3 .

**Hosting institution:** The Centre for Autonomous Systems (CAS) is an inter-departmental research centre at KTH, Stockholm, Sweden. The Centre has studied intelligent systems since 1996. The main research aspect is robotic systems as assistants to people for everyday tasks in everyday environments. Operational systems have been implemented in the area of service robots for domestic applications. To facilitate such research the centre has integrated research across control engineering, systems modeling, perception, artificial intelligence and mechanical designinvolving researchers from the departments of electrical engineering, computer science, mathematics and mechantronics.

The project PI has been active in the field of human-robot interaction since 2004, and have made contributions ranging from low-level motion prediction for interfaces[35] to socialrobot interaction[36]. The participants furthermore have made several contributions to real-time adaptive estimation, with significant both theoretical and experimental results[37,38].

[35]Christian Smith and Henrik I Christensen. "A Minimum Jerk Predictor for Teleoperation with Variable Time Delay", IEEE/RSJ International Conference on Intelligent Robots and Systems. pp 5621-5627, 2009

[36]Noriaki Mitsunaga, Christian Smith, Takayuki Kanda, Hiroshi Ishiguro, and Norihiro Hagita, "Adapting Robot Behavior for Human-Robot Interaction", IEEE Transactions on Robotics, vol 24, issue 4, Aug 2008. pp. 911–916

[37]Yiannis Karayiannidis, Christian Smith, Francisco Vina, Petter Ögren, and Danica Kragic. " 'Open Sesame!' - Adaptive Force/Velocity Control for Opening Unknown Doors." IEEE/RSJ International Conference on Intelligent Robots and Systems, 2012 Vilamoura, Portugal, pp. 4040-4047

[38]Yiannis Karayiannidis, Christian Smith, Francisco Vina, Petter Ögren, and Danica Kragic. "Model-free robot manip-

The research group also brings expertise in visual servoing, vision for human action estimation and robotic grasping[39], reconstruction of human motion[40,41], grasping and manipulation[42], providing some of the necessary building blocks for implementing the object handover tasks. Finally, CAS has a long tradition in system integration for full scale, sensor intense, operational systems[43,44,45]. We are therefore well prepared to take on the challenges posed not only theoretically but also technologically.

# 8 International and National Collaboration

The Centre for Autonomous Systems has support from the Swedish Foundation for Strategic Research and The Swedish Research Council. The group has participated in the EU projects CogVis, Insight2+ and VIBES, MOBVIS, Cogniron, Cosy, Neurobotics, EURON-II, Muscle, Pascal, GRASP, CogX and PACO-PLUS. The laboratory is currently involved in the FP7 projects eSMCs, TOMSY, Robo-How.cog, and Reconfig, and the Horizon2020 projects RobDream, SaraFUN, Strands, and Trader. The research planned in this project is complementary to the other activities within the center, and will significantly benefit from the ongoing projects as most of the hardware is already available and there are groups working on related problems. There are currently around 40 members in the CAS group and additionally 10-15 master level students. CAS maintains a large number of collaborations with international academic institutions in robotics and vision. The PI is also involved in initiating new local and national collaborations, such as the Centre for Biomechanics at KTH, and the Vinnova workshops on social robotics.

**Dissemination and training:** We will also work with dissemination activities to 1) initiate and support an intensive scientific collaboration within the project and with other ongoing projects, both nationally and internationally, 2) enable a continuous exchange with related research communities through publication at top conferences and journals in the field, 3) bridge to and involve industry where relevant, 4) obtain feedback from potential future "non-commercial" users, and 5) reach out to the general public. The group has organized several workshops and tutorials at the top conferences in the field and we will continue this as an integral part of this project. The student will also particiapte at the summer schools organized by the EU projects that CAS is involved in, thus providing the necessary interaction and collaboration outside this project.

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ulation of doors and drawers by means of fixed-grasps," IEEE International Conference on Robots and Automation, 2013, Karlsruhe

[39] K. Huebner, M. Bjorkman, B. Rasolzadeh, M. Schmidt and D. Kragic. Integration of Visual and Shape Attributes for Object Action Complexes. In ICVS08: International Conference on Computer Vision Systems, 2008.

[40] H. Kjellstrom, J. Romero, D. Martinez and D. Kragic. Simultaneous Visual Recognition of Manipulation Actions and Manipulated Objects, In European Conference on Computer Vison 2008.

[41] V. Kruger, D.L. Herzog, Sanmohan, A. Ude, D. Kragic, Learning Actions from Observations, Robotics and Automation Magazine, Volume 17, Issue 2, pp 30-43, 2010

[42] K. Huebner, S. Ruthotto, and D. Kragic. "Minimum Volume Bounding Box Decomposition for Shape Approximation in Robot Grasping", *IEEE Int. Conf. on Robotics and Automation*, 2008.

[43] Christian Smith and Henrik I Christensen. Robot Manipulators - Constructing a High Performance Robot from Commercially Available Parts IEEE/RAS Robotics and Automation Magazine, Vol 16:4, pp. 75-83, Dec 2009

[44] Christian Smith and Yiannis Karayiannidis. "Optimal Command Ordering for Serial Link Manipulators" IEEE-RAS International Conference on Humanoid Robots, Nov 29 - Dec 1, 2012, Osaka. pp 255-261

[45] Lars Petersson, Patric Jensfelt, Dennis Tell, Morten Strandberg, Danica Kragic, Henrik I. Christensen, "Systems integration for real-world manipulation tasks", IEEE International Conference on Robotics and Automation, 2002, pp. 2500-2505

## 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

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## 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 | PhD Student | NN | 100 |
| 2 | Applicant | Christian Smith | 25 |

#### Salaries including social fees

| | Role in the project | Name | Percent of salary | 2016 | 2017 | 2018 | 2019 | Total |
|---|---|---|---|---|---|---|---|---|
| 1 | Applicant | Christian Smith | 25 | 188,000 | 193,000 | 198,000 | 203,000 | 782,000 |
| 2 | Other personnel without doctoral degree | Doktorand | 100 | 534,000 | 587,000 | 646,000 | 711,000 | 2,478,000 |
| | Total | | | 722,000 | 780,000 | 844,000 | 914,000 | 3,260,000 |

### 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 | Kontor | 87,000 | 94,000 | 102,000 | 110,000 | 393,000 |
| | Total | 87,000 | 94,000 | 102,000 | 110,000 | 393,000 |

### Running Costs

| | Running Cost | Description | 2016 | 2017 | 2018 | 2019 | Total |
|---|---|---|---|---|---|---|---|
| 1 | resor | konferenser, mm | 40,000 | 40,000 | 40,000 | 40,000 | 160,000 |
| 2 | Datorer | | 40,000 | | | | 40,000 |
| | Total | | 80,000 | 40,000 | 40,000 | 40,000 | 200,000 |

### 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 | 722,000 | 780,000 | 844,000 | 914,000 | 3,260,000 | | 3,260,000 |
| Running costs | 80,000 | 40,000 | 40,000 | 40,000 | 200,000 | | 200,000 |
| Depreciation costs | | | | | 0 | | 0 |
| Premises | 87,000 | 94,000 | 102,000 | 110,000 | 393,000 | | 393,000 |
| Subtotal | 889,000 | 914,000 | 986,000 | 1,064,000 | 3,853,000 | 0 | 3,853,000 |
| Indirect costs | 375,000 | 405,000 | 438,000 | 475,000 | 1,693,000 | | 1,693,000 |
| Total project cost | 1,264,000 | 1,319,000 | 1,424,000 | 1,539,000 | 5,546,000 | 0 | 5,546,000 |

## Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

### Explanation of the proposed budget*

Arbetet i projektet bedrivs av projektledaren tillsammans med en doktorand. För dessa behövs löner, lokaler och datorer för att kunna utföra arbetet. Vidare behövs två årliga resor till vetenskapliga konferenser för att sprida resultaten och interagera med det veteskapliga samhället. Kostnader för övrig utrustning och laboratorielookaler täcks från Centrum för Autonoma System, och belastar inte detta projekt.

## 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

## Personal Data



| | | | |
|---|---|---|---|
| **Name:** | Christian Smith | **Phone:** | +46 (0)8 790 67 28 |
| **Born:** | Stockholm, Sweden, August 28 1975 | **Fax:** | +46 (0)8 723 03 02 |
| **Affiliation:** | KTH CSC - CAS/CVAP SE-100 44 Stockholm, Sweden | **E-mail:** | ccs@kth.se |
| | | **URL:** | www.cas.kth.se/~ccs |



**1. Högskoleexamen / Higher education qualification(s)**
2005, MSc in Engineering Physics (Civilingengör i teknisk fysik)
KTH – Royal Institute of Technology
Thesis title: "Behavior Adaptation for a Socially Interactive Robot"
Supervisor: Prof. Henrik Christensen

**2. Doktorsexamen / Doctoral degree**
2009, PhD in Computer Science – Robots and autonomous systems
KTH – Royal Institute of Technology
Thesis title: "Input Estimation for Teleoperation"
Supervisor: Prof. Patric Jensfelt

**3. Relevanta postdoktorsvistelser / Post doctoral activites**

2010-2011 Advanced Telecommunications Research Int. (ATR), Kyoto, Japan

**4. Docentkompetens**: *in application*

**5. Nuvarande anställning / Current employment**

| | |
|---|---|
| 2014 – present | Assistant Professor, Computer Vision and Active Perception Lab, School of Computer Science and Communication, KTH (75% research) |

**6. Tidigare anställningar / Previous employments**

| | |
|---|---|
| 2011–2013 | Researcher, Centre for Autonomous Systems (CAS), KTH, Stockholm, Sweden |
| 2010–2011 | Research Scientist, ATR, Kyoto, Japan |
| 2010 | Researcher, CAS, KTH |
| 2005 – 2009 | PhD candidate, CAS, KTH |
| 2004 | Research Intern, ATR, Kyoto, Japan |
| 2002 – 2005 | Teaching assistant, NADA, KTH |

**7. Uppehåll i forskningen (Interruption in research)**

| Period | Portion | Total |
|---|---|---|
| 1/1–30/6 2008 | 50% | 3 months |
| 1/1-30/3 2010 | 100% | 3 months |
| 1/4-30/5 2010 | 60% | 5 weeks |

**8. Handledning (Supervision)**

Francisco Vina (PhD student, co-supervisor, 2012-2016)
Rakesh K. Thekkeparampumadom (PhD student, co-supervisor, 2014-2018)
Nauman Masud (PhD student, co-supervisor, 2014-2018)

**9. Eventuell övrig information av betydelse för ansökan (Other information of relevance to the application)**

**Current projects:**
**RobDREAM**: Optimising Robot Performance while Dreaming, ICT-23-2014 Robotics call, EU Horizon2020 (2015–2018).
**RoboHow.Cog**: Web-enabled and Experience-based Cognitive Robots that Learn Complex Everyday Manipulation Tasks, Cognitive Systems and Robotics Initiative, EU FP7 IP (2012–2015).

**Other academic activities:**
**Secretary** of IEEE Robotics and Automation Society, Sweden Chapter.
**Financial Chair**: IEEE International Conference on Robotics and Automation, 2016.
**Journal Reviewer**: IEEE Transactions on Robotics, Journal of Robotics, Journal of Human-Robot Interaction, Safety Science Monitor, and Robotics, and Computer Integrated Manufacturing, etc.
**Associate Editor**: Associate editor for IROS 2015.
**Conference Reviewer**: RSS, ICRA, IROS, HRI, ROMAN, SYROCO, ICSR, AIM, and others.
**Session chair** for session on Force Control at IEEE/RSJ International Conference on Intelligent Robots and Systems, October 10, 2012 Vilamoura, Portugal
**Co-organizer** of invited session in IFAC Symposium in Robot Control Invited session title: *"Mobile manipulation for household applications"*.

## Publication list

# Publication list 2006-2014

## Christian Smith

*Total number of citations by Google Scholar: 295, h=10.* Papers most relevant to the project are marked with an '*'.

### 1. Peer-reviewed original articles

**J1*.** Christian Smith and Patric Jensfelt. "A Predictor for Operator Input for Time-Delayed Teleoperation." *Mechatronics*, special issue on Design Control Methodology, Vol 20:7, pp. 778-786, Oct 2010

**J2.** Christian Smith and Henrik I Christensen. "Robot Manipulators - Constructing a High Performance Robot from Commercially Available Parts" *IEEE/RAS Robotics and Automation Magazine*, Vol 16:4, pp. 75-83, Dec 2009

**J3.** Noriaki Mitsunaga, Christian Smith, Takayuki Kanda, Hiroshi Ishiguro, and Norihiro Hagita. "Adapting Robot Behavior for Human-Robot Interaction" *IEEE Transactions on Robotics*, vol 24, issue 4, pp 911-916, Aug 2008.

**J4*.** Christian Smith, Mattias Bratt, and Henrik I Christensen. "Teleoperation for a Ballcatching Task with Significant Dynamics" *Neural Networks*, Special Issue on Robotics and Neuroscience, vol 24, issue 4, pp. 604-620, May 2008.

**J5.** Noriaki Mitsunaga, Christian Smith, Takayuki Kanda, Hiroshi Ishiguro, and Norihiro Hagita. "Robot Behavior Adaptation for Human-Robot Interaction based on Policy Gradient Reinforcement Learning" *Journal of the Robotics Society of Japan*, vol. 24, no. 7, pp.820-829, 2006.

### 2. Peer-reviewed conference contributions

**C1.** Yiannis Karayiannidis, Christian Smith, and Danica Kragic. "Mapping Human Intentions to Robot Motions via Physical Interaction Through a Jointly-held Object." *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, Edinburgh, Scotland, UK, Aug 25-29, 2014.

**C2.** Yuquan Wang, Francisco Vina, Yiannis Karayiannidis, Christian Smith, and Petter Ögren. "Dual Arm Manipulation using Constraint Based Programming." *IFAC World Congress*, Cape Town, South Africa, Aug 24-29, 2014

**C3.** Yiannis Karayiannidis, Christian Smith, Francisco Vina, and Danica Kragic. "Online Contact Point Estimation for Uncalibrated Tool Use." *IEEE International Conference on Robots and Automation (ICRA 2014)*, Hong Kong, China, pp 2488-2493

**C4.** Alejandro Marzinotto, Michele Colledanchise, Christian Smith, and Petter Ögren. "Towards a Unified Behavior Trees Framework for Robot Control." *IEEE International Conference on Robots and Automation (ICRA 2014)*, Hong Kong, China, pp 5420-5427

**C5*.** Yiannis Karayiannidis, Christian Smith, Francisco Vina, and Danica Kragic. "Online Kinematics Estimation for Active Human-Robot Manipulation of Jointly Held Objects." *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, November 3-7, 2013 Tokyo, Japan. pp 4872-4878

**C6.** Francisco Vina, Yasemin Bekiroglou, Christian Smith, Yiannis Karayiannidis, and Danica Kragic. "Predicting Slippage and Learning Manipulation Affordances through Gaussian Process Regression." *IEEE-RAS International Conference on Humanoid Robots*, Oct 15-17, 2013, Atlanta. pp 462-468

**C7.** Xavi Gratal, Christian Smith, Mårten Björkman, and Danica Kragic. "Integrating 3D Features and Virtual Visual Servoing for Hand-Eye and Humanoid Robot Pose Estimation." *IEEE-RAS International Conference on Humanoid Robots*, Oct 15-17, 2013, Atlanta. pp 240-245

**C8*.** Chao Shi, Masahiro Shiomi, Christian Smith, Takayuki Kanda, and Hiroshi Ishiguro. "A model of distributional handing interaction for a mobile robot." *Robotics Science and Systems, RSS2013*, Berlin, Germany.

**C9.** Chao Shi, Masahiro Shiomi, Christian Smith, Takayuki Kanda, and Hiroshi Ishiguro. "Machikado no hokousha ni chirashi wo kubaru robotto (Japanese)" *31st Annual Conference of the Robotics Society of Japan (RSJ2013)* 1G3-07, September 2013.

**C10.** Chao Shi, Masahiro Shiomi, Christian Smith, Takayuki Kanda, and Hiroshi Ishiguro. "A model of handing interaction towards a pedestrian." *Proceedings of the 8th ACM/IEEE international conference on Human-robot interaction (HRI'13)*, Tokyo, Japan, March 3–6 2013, pp. 415-416

**C11.** Yiannis Karayiannidis, Christian Smith, Francisco Vina, Petter Ögren, and Danica Kragic. "Model-free robot manipulation of doors and drawers by means of fixed-grasps." *IEEE International Conference on Robots and Automation* Karlsruhe, May 2013.

**C12.** Christian Smith and Yiannis Karayiannidis. "Optimal Command Ordering for Serial Link Manipulators" *IEEE-RAS International Conference on Humanoid Robots*, Nov 29 - Dec 1, 2012, Osaka. pp 255-261

**C13.** Yiannis Karayiannidis, Christian Smith, Francisco Vina, Petter Ögren, and Danica Kragic. " 'Open Sesame!' - Adaptive Force/Velocity Control for Opening Unknown Doors." *IEEE/RSJ International Conference on Intelligent Robots and Systems*, October 7-12, 2012 Vilamoura, Portugal, pp. 4040-4047

**C14.** Yiannis Karayiannidis, Christian Smith, Francisco Vina, Petter Ögren, and Danica Kragic. "Design of force-driven online motion plans for door opening under uncertainties." *Workshop on Real-time Motion Planning: Online, Reactive, and in Real-time*, 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, October 12, 2012 Vilamoura, Portugal

**C15.** Yiannis Karayiannidis, Christian Smith, Petter Ögren, and Danica Kragic. "Adaptive Force/Velocity Control for Opening Unknown Doors." *IFAC Symposium on Robot Control, SyRoCo* 5-7 Sep. 2012, Dubrovnik, Croatia.

**C16.** Petter Ögren, Christian Smith, Yiannis Karayiannidis, and Danica Kragic. "A Multi Objective Control approach to Online Dual Arm Manipulation." *IFAC Symposium on Robot Control, SyRoCo* 5-7 Sep. 2012, Dubrovnik, Croatia.

**C17.** Christian Smith and Henrik I Christensen. "A Minimum Jerk Predictor for Teleoperation with Variable Time Delay" *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).* pp 5621-5627, 2009.

**C18*.** Christian Smith and Henrik I Christensen. "Wiimote Robot Control Using Human Motion Models" *IEEE International Conference on Intelligent Robots and Systems (IROS).* pp 5509-5515, 2009

**C19.** Mattias Bratt, Christian Smith and Henrik I Christensen. "Minimum Jerk Based Prediction of User Actions for a Ball Catching Task" *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).* pp 2710-2716, 2007

**C20.** Christian Smith and Henrik I Christensen. "Using COTS to Construct a High Performance Robot Arm" *IEEE International Conference on Robots and Automation (ICRA).* pp 4056-4063, 2007

**C21.** Mattias Bratt, Christian Smith and Henrik I Christensen. "Design of a Control Strategy for Teleoperation of a Platform with Significant Dynamics" *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS).* pp 1700-1705, 2006

## 3. Monographs

**M1.** Christian Smith. "Input Estimation for Teleoperation" *PhD Thesis*, KTH – Royal Institute of Technology, 2009

## 4. Research review articles

**R1.** Christian Smith, Yiannis Karayiannidis, Lazaros Nalpantidis, Xavi Gratal, Peng Qi, Dimos Dimarogonas, and Danica Kragic. "Dual Arm Manipulation - a Survey." *Robotics and Autonomous Systems*, Vol 60, no 10, pp. 1340-1353, 2012

## 5. Books and book chapters

**B1.** Noriaki Mitsunaga, Christian Smith, Takayuki Kanda, Hiroshi Ishiguro, and Norihiro Hagita. "Adapting Nonverbal Behavior Parameters to be Preferred by Individuals" in *Human-Robot Interaction in Social Robotics*, T. Kanda and H. Ishiguro, eds. CRC Press, 2012. ISBN 978-1466506978. pp 312-324

**CV**

| | |
|---|---|
| **Name:** Christian Smith | **Doctorial degree:** 2009-12-30 |
| **Birthdate:** 19750828 | **Academic title:** Doktor |
| **Gender:** Male | **Employer:** Kungliga Tekniska högskolan |

## Research education

### Dissertation title (swe)

### Dissertation title (en)

Input Estimation for Teleoperation

| Organisation | Unit | Supervisor |
| --- | --- | --- |
| Kungliga Tekniska Högskolan, Sweden<br>Sweden - Higher education Institutes | CVAP, Datorseende och robotik | Patric Jensfeldt |

| Subject doctors degree | ISSN/ISBN-number | Date doctoral exam |
| --- | --- | --- |
| 10207. Datorseende och robotik (autonoma system) | 1653-5723 | 2009-12-30 |

## Publications

| | |
| --- | --- |
| **Name:** Christian Smith | **Doctorial degree:** 2009-12-30 |
| **Birthdate:** 19750828 | **Academic title:** Doktor |
| **Gender:** Male | **Employer:** Kungliga Tekniska högskolan |

Smith, Christian 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.*