Application

2015-03-31

2015-04342	Åström, Karl	NT-14

Information about applicant

Name: Karl Åström

Doctorial degree: 1996-05-30

Birthdate: 19670218

Academic title: Professor

Gender: Male

Employer: Lunds universitet

Administrating organisation: Lunds universitet

Project site: Matematikcentrum 107150

Information about application

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Project title (english): Robust geometry estimation from audio, video, radio and wifi

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Classification code: 10207. Datorseende och robotik (autonoma system), 20205. Signalbehandling

Keywords: Computer vision, Computational Audio, Node-calibration, time-of-arrival, time-difference-of-arrival

Funds applied for

Year:	2016	2017	2018	2019
Amount:	1,269,000	1,305,000	1,340,000	1,378,000

Descriptive data

Project info

Project title (Swedish)*

Robust geometriskattning från ljud, bilder, radio och wifi

Project title (English)*

Robust geometry estimation from audio, video, radio and wifi

Abstract (English)*

Many problems in computer vision and in audio/radio based positioning are inverse problems or parameter estimation problems. Typically the forward problem, although non-linear, are well understood. In vision each detected image point can be seen as a measurement of the direction to a 3D point. In audio/radio measurements can be rephrased as distance measurements. In both of these settings, the inverse problem of calculating the camera motion and scene structure or calculating anchor-free receiver positions and transmitter positions can be quite challenging. In particular it is difficult to establish matching between points in images and between time instants in audio/radio signals. The aim of this project is to develop computationally efficient, numerically stable and robust techniques for solving navigation and localization problems using audio/radio/video/wifi. In particular we are interested in (i) developing improved techniques for solving systems of polynomial equations, (ii) developing geometric understanding and computational algorithms for solving minimal geometric problems involving distance (radio, audio) or directional (vision), (iii) developing robust methods for non-minimal (over-determined) geometric problems and (iv) developing large scale map-making systems (SLAM, structure from motion, anchor free localization) algorithms based on real data (audio/radio/video/wifi). We believe that such a development will be an enabler for applications in industry

Popular scientific description (Swedish)*

Om man tar flera bilder av samma föremål, så är det relativt enkelt att räkna ut föremålets form om man vet var man stod när man tog bilderna. På samma sätt är det relativt enkelt att räkna ut var man har tagit en bild om man vet föremålets form. Det är välkänt, men ganska överraskande, att man kan räkna ut både föremålets form och de positioner från vilka bilderna är tagna trots att man inte har någon information mer än bilderna. På samma sätt kan man i princip från ett antal ljudinspelningar, räkna ut både var mikrofonerna varit placerade och från vilka positioner ljud har genererats. Sådana metoder kallas kartering, SLAM (Simultanaous Localization and Mapping), ankarfri lokalisering eller för struktur och rörelseproblemet. Det visar sig att det i praktiken är svårt att konstruera datorprogram, som kan göra allt detta automatiskt och under generella ljud/bild-förhållanden. En av svårigheterna är att man behöver automatiska metoder för att hitta samma punkter i två bilder eller samma ljud-del i två ljudinspelningar. Man behöver dessutom göra detta med hög precision för att få bra resultat. De metoder som existerar är bristfälliga. Det innebär i sin tur att man i senare skede måste hitta och ta bort dessa felaktigheter. Man brukar säga att metoderna måste vara robusta. Detta forskningsprojekt handlar om grundforskning, som behövs för att utveckla sådana robusta metoder. I projektet vill vi lösa svåra problem, som uppkommer när man ska konstruera sådana metoder. Dels vill vi vidareutveckla metoder för att lösa system av polynomekvationer på ett effektivt sätt. För så kallade linjära ekvationssystem i flera variabler, finns det en mycket välutvecklad teori (linjär algebra) och mycket effektiva datorprogram (numerisk linjär algebra). Det gör att sådana metoder fått bred användning i många tekniska och naturvetenskapliga discipliner. Om man gör ekvationerna aningen mer komplicerade och tillåter produkter av obekanta, så får man istället system av polynomekvationer i flera obekanta. Detta är också ett område som är relativt väl studerat inom matematiken (algebraisk geometri). På senare år har det utvecklats tekniker för att lösa även sådana ekvationer snabbt och med stor precision, åtminstone om det inte är för många obekanta och för komplicerade ekvationer. Dessa lösningsmetoder är viktiga i många sammanhang.Inom projektet vill vi sedan arbeta med att lösa så kallade minimala karteringsproblem. Detta är de frågeställningar med så lite information som möjligt, som fortfarande går att lösa. Lösningar på dessa minsta problem är viktiga komponenter, som används som byggstenar för de system som vi inom projektet vill utveckla. Vi har gjort prototypsystem för bilder och hoppas kunna göra prototypsystem för ljud, ultraljud, radio och wifi. Vi ser positivt på synergieffekterna i samspel med andra projekt, t ex finansierade av Vinnova och EU. Det finns ett stort intresse för dessa frågor i industrin. Apple köpte det svenska företaget C3 Technologies för att kunna göra bättre 3D modeller av städer för något år sedan. Apple köpte nyligen ett litet företa WifiSLAM för att kunna göra bättre kartor baserat på wifi. Även Google och Nokia satsar på området. Här i Sverige arbetar Sony Mobile på liknande frågor. Det finns också flera mindre bolag, Combain Mobile AB, SenionLab med flera.

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*

1. Naturvetenskap > 102. Data- och informationsvetenskap (Datateknik) > 10207. Datorseende och robotik (autonoma system)

2. Teknik > 202. Elektroteknik och elektronik > 20205. Signalbehandling

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

Keyword 1*

Computer vision

Keyword 2*

Computational Audio

Keyword 3*

Node-calibration

Keyword 4

time-of-arrival

Keyword 5

time-difference-of-arrival

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*

I projektet ingår ingen hantering av persondata, inga djurförsök och inga humanförsök. Experimenten kommer i huvudsak att ske vid ett nystartat positioneringslab vid MAPCI i Lund.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

A: Research Plan and constellation

Purpose and aims

Map-making, localization and navigation covers a broad application area, ranging from traditional needs in the terrestrial, aerial and naval transport sectors to personal objectives of finding your way to school if you are visually impaired, to the nearest fire exit in case of an emergency, or to specific goods in your local supermarket. Many potential applications are however presently hindered by performance limitations of existing techniques for map-making and localization. The project goal is to make significant progress in mathematical tools (optimization and algebraic geometry), in methods (solutions to minimal problems, systems for map-making and localization) and in applications using radio/audio/vision/wifi etc.

The timing is excellent for this research effort for several reasons. One is the recent improvement in sensor hardware technology making high-performance systems possible out of low-performance components. Examples include high-resolution cameras, gyros, accelerometers and compass MEMS sensors increasingly used in mobile phones, in some cases being agreed on as mandatory for e.g. iPhone and Android products. Also GPS and in particular wifi receivers with low power consumption are becoming smaller and widely available. Global databases are emerging making for instance available information about the position of most cellular and wireless LAN base stations. However, such databases are not accurate indoors, because of the limitations of GPS signal penetration.

This project proposal is three-tiered, cf. Figure 2. On a basic mathematical layer the focus is to advance the mathematics of algebra/geometry and within large-scale structured optimization problems. Within Algebra/geometry the research concerns solution methods for systems of polynomial equations and solutions to certain classes of geometrics problems that arise in application areas. Within a method development layer, the aim is to develop computationally efficient and numerically stable and robust techniques for solving map-making, navigation and localization problems using a multitude of different measurement types (audio, radio, video, wifi, magnetometers, accelerometer, gyro) either separately or in combination. Here robustness and high tolerance to outliers is important. On an application layer, we are interested in developing and testing such algorithms and methods on real data. There are numerous potential applications. For some of these applications there are already interested users within Swedish industry. For some, there are potential for future start-up companies.

Project description

In more general terms the project is about developing new theory, new tools and new prototype systems for map-making and localization/navigation using directional data (vision), distance data (sound, ultrasound, radio, wifi) and other sensor modalities. In this section we first present some examples, to indicate the variety of applications that share the same methodological core. Then follows a description of the work plan in three work packages, cf. Figure 2.

Multi-path anchor-free radio-based localization: In top-left of figure 1 is shown an experiment with 1 radio transmitter and 1 moving radio receiver. We have shown in our research, [32], that it is possible to determine the position of the receiver with centimeter precision using this setup. As a side effect we are also able to determine the shape of the room. The signal from the transmitter is reflected e.g. in walls. This corresponds to having multiple (reflected) radio transmitters in unknown location. This is possible because of new algorithms that neither require neither known receiver positions nor known transmitter positions. Such components can become integral technology components for future mobile phones or internet-of-things.

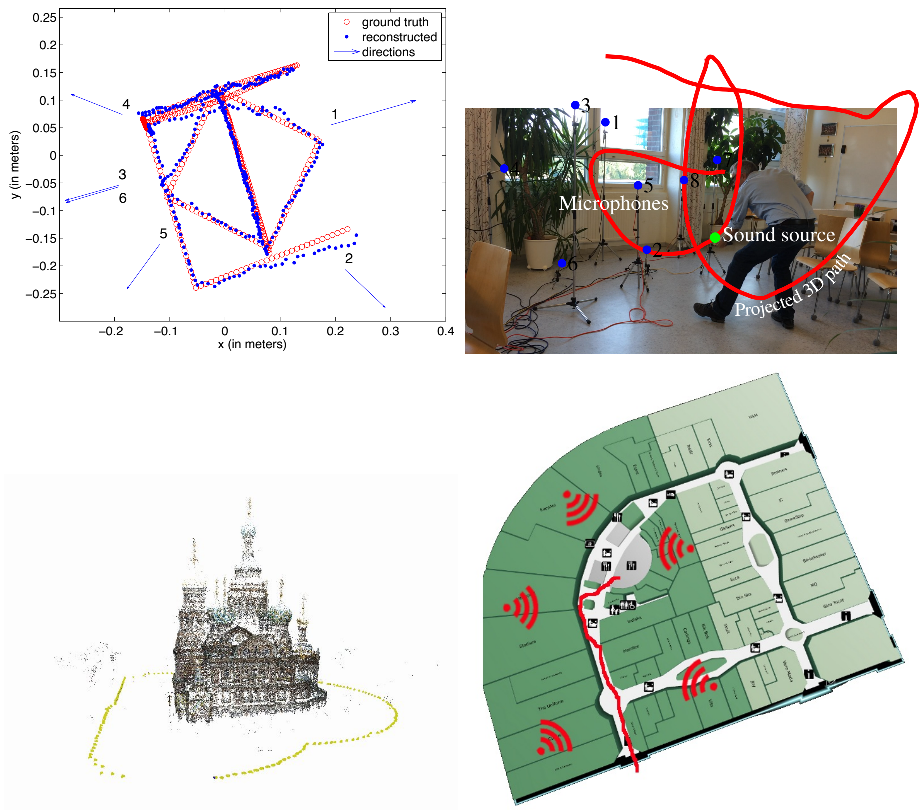

Figure 1: Top-left: Centimetre positioning of a mobile radio antenna using a singe radio transmitter and a single radio receiver using multi-path propagation. Top-right: Multi-microphone calibration, sound localization and room estimation using ambient sound. Bottom-left: 3D reconstructed camera path and model using images. Bottom-right: Global indoor localization using wifi signal strength.

Multi-microphone calibration: In top-right of figure 1 is shown an experiment with 8 microphones. Using ambient sound, we have shown in recent papers [30, 11, 33, 28], using new mathematical tools and methods for solving systems of polynomial equations, [17, 3], how map-making systems can be used to determine both the unknown 3D location of the microphones and the unknown locations and timings of the distinct sound sources and the shape of the room. Such systems can be used for on-the-fly calibration of multi-microphone setups, which then enables beam forming or tracking of speakers, animals or other objects. Such components can be used to enable calibration free sound processing in e.g. teleconference applications.

Image based 3D reconstructions: In bottom-left of figure 1 is shown a 3D reconstruction based on images. There has been an intense development of technologies for such systems. In this development the researchers behind this project proposal have been an integral part. An example on how such systems work are shown in the clip: `http://www.youtube.com/watch?v=i7ierVkXYa8`. Although we have come a long way in making such systems work, there are still many open research questions. From an application view, there are many open questions on how to work efficiently with large-scale (city-wide/world-wide) data. There are also many interesting research questions for bridging aerial, outdoor and indoor images for seamless reconstructions from aerial, outdoor and indoor locations.

Wifi signal strength maps and localization: Wifi signal strength measurements gives, although very noisy, distance measurements from measurement positions to wifi unit positions. Using map-making systems it is possible to determine all wifi-positions worldwide, to determine signal diminishing barriers and measurements positions. There are many interesting and challenging research questions in this area. Current state-of-the-art requires known measurement positions, usually using GPS, which only works outdoors. Other approaches require special calibration methods involving, e.g. hand-clicked ground truth positions for some of the measurement positions or involving new measurements along a pre-defined path. None of these current methods allow global indoor positioning. Using the results within this research proposal we aim at developing solve methods that allow for global indoor localization. This is illustrated in the bottom-right of figure 1.

Other examples of use of such systems are: visual and laser based real-time map-making for autonomous navigation of helicopters (collaboration with P. Doherty, Linköping University), minimal problems for magnetometer map-making and localization (collaboration with F. Gustafsson, Linköping University), Scene calibration and map-making for pan-tilt-zoom cameras for sport analysis (collaboration with Spiideo AB), insect and bird tracking (collaboration with CANMOVE, Lund University), animal tracking and analysis (collaboration with CAMVIS, Lund University), vision for sport analysis, based on multi-camera network (new start-up).

Work plan

In all of the map-making problems above there is a bipartite structure (e.g. senders vs receivers, cameras vs scene structure). In this project we would like to exploit these similarities and develop methods relevant for all of these applications as well as disseminate solutions within one application area to the other. Within different disciplines, slightly different notations are used. The problem is often referred to as the structure and motion problems, structure from sound, SLAM (Simultaneous Localization and Mapping) or anchor-free node-localization. In this project proposal we will use the term map-making to denote this, irrespective of application area.

An overview of the work plan is shown in Figure 2. The work has three layers (Applications, Methods and Mathematical core). The work plan is divided in three work-packages.

The first work-package concerns sensors, applications and dissemination. These build on the methods and mathematics developed within work package 2 (optimization and map-making systems) and work package 3 (algebraic geometry and minimal problems). For example, the minimal problem solvers build on the algebraic geometry tools developed. The minimal solvers are used as an integral part of the global optimization methods and the robust optimization methods in WP2. The minimal solvers are also used to obtain initial estimates for the iterative optimization methods.

WP 1: Applications - Sensors and system development

WP 1.1 Sensors and data

Within the project we are dealing with several types of experimental data. When it comes to equipment, the most important part is the access to real data of different sensor modalities. Here comes a brief description of such sensor modalities.

Images. The mathematical imaging group has extensive experience of working with images and video in numerous aspects of computer vision and image analysis.

Sound. The consortium has already produced new research results conceding sound-based map-making. For sound related research, we have additional competences at the centre e.g. Sören Vang Andersen, newly recruited from Skype to the centre for mathematical sciences, Andreas Jacobsson, mathematical statistics and Mikael Nilsson, recruited from the sound research group at BTH.

Radio. For experiments on radio-signals we have access to state-of-the-art research capabilities at the department for electrical and information technology at Lund University, through collaboration

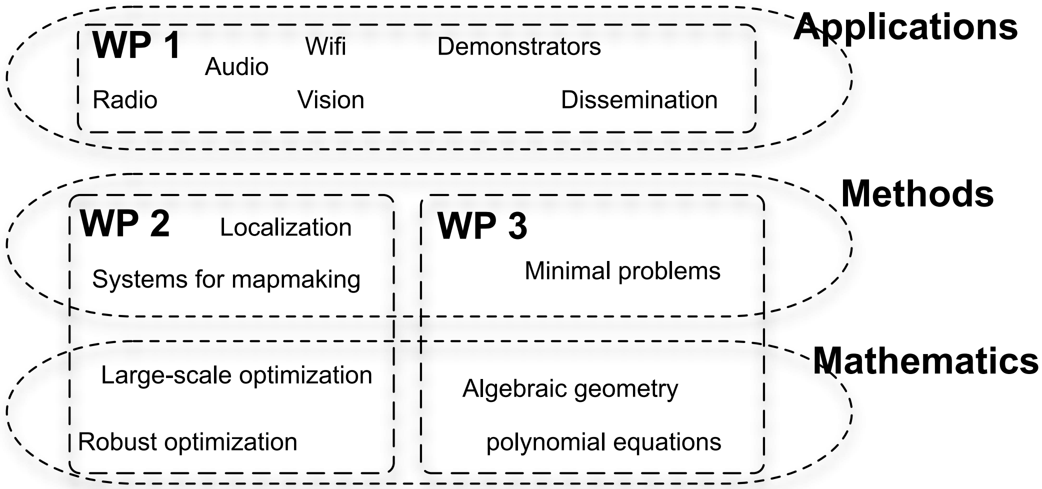

Figure 2: The project is divided into three work packages. Workpackage 1 concerns sensors and applications. Workpackage 2 contains both developments in mathematics (optimization) and method development in building map-making systems. Workpackage 3 also has a mathematical core in mathematics (algebraic geometry) and method development in solving minimal problems for structure and motion.

with Fredrik Tufvesson within the ELLIIT research project.

Wifi. Within wifi-slam we are fortunate to have close collaborations with Sony Mobile AB and Combain AB. Within the collaborative project 'Global inomhuspositionering med hög noggrannhet' funded by Vinnova, we have access to a global dataset of 5 billion signal strength measurements to 400 million wifis.

We have recently begun to set up a positioning laboratory at MAPCI (the Mobile And Pervasive Computing Institute). This centre is part of the university and is located close to Sony, Ericsson, Sigma Connectivity and numerous startups. At the laboratory we have a good testbed for validating different mapping and localization techniques using audio, radio and vision.

WP 2 Optimisation and large-scale robust structure from motion systems

WP 2.1 Non-sequential methods for computing large-scale reconstructions

Since the entire structure from motion problem (from matching to geometry computation) cannot be solved in a single step different methods for the involved subproblems have to be combined into a larger framework. Subproblems can be solved using optimization and algebraic solvers (WP 2.2, 2.3 and 3). WP 2.1 deals with the problem of combining the basic methods in an optimal way, so that the system can robustly handle models with thousands to millions of images taken under general conditions.

Here we are interested in both sequential methods and non-sequential methods. One line of research build upon promising recent work on non-sequential methods, [34] , where rotational consistency and robust estimation using convex optimization were used. The resulting system is more robust with respect to (i) unreliable two-view estimations caused by short baselines, (ii) repetitive scenes with locally consistent structures that are not consistent with the global geometry and (iii) loop closing as errors are not propagated in a sequential manner.

Another line of research is that of methods for robust detection and tracking of time-differences in real multi-channel data from an reverbant environment. Promising progress has been made recently, cf. [35]. This is an area, where there is great potential for further improvement on the current state-of the art. Together with improvements on robust estimation of geometry, this will allow for flexible and robust systems for map-making under a wide variety of settings.

WP 2.2 Exploiting structure in large-scale optimisation

Modern structure from motion (SfM) systems, which compute cameras and 3D structure from images, rely heavily on bundle adjustment. Bundle adjustment refers to the iterative refinement of camera and 3D point parameters based on minimization of the sum of squared reprojection errors and hence belong to the class of non-linear least squares problems. Bundle adjustment is important both as a final step to polish off a rough reconstruction obtained by other means as well as a way of avoiding accumulation of errors during an incremental reconstruction procedure.

A recent trend in SfM applications is to move from small and medium size setups to large-scale problems (typically in the order 10^3-10^4 cameras or more), *cf.* [1, 37, 20]. Bundle adjustment in general has $\mathcal{O}(N^3)$ complexity, where N is the number of variables in the problem [23]. For large problems, bundle adjustment hence starts to become a major computational bottleneck. In this workpackage we intend to improve techniques for large-scale and possible distributed optimization of information intensive mapping problems, not only for image data, but also for radio-based navigation. Ultimately the goal would be to develop techniques that scale roughly linearly with size of data so that it could be feasible to optimize over massive data, such as all the images in the world or all signal strengths of all mobile units in the world. From [14] a key observation is that for a certain class of problems there is in fact a roughly linear increase in time and memory complexity for direct methods. For another class of mapping problems linear complexity is obtained with conjugate gradient methods.

In this workpackage we will:

- Develop new algorithms for pre-conditioning Conjugate-Gradient using skeletal graphs
- Develop new understanding of computational complexity of iterative algorithms with additional measurements such as approximate positions at key points.
- Transfer of optimization techniques for large scale bundle adjustment to large scale radio based mapping from sensor networks

WP 2.3 Global and robust optimization methods

One difficulty of the map-making problem is that it can be difficult a priori to establish correspondences between data points in images and between time instants in audio/radio signals. However, within computer vision the following paradigm has proved to be useful both in theory and in practice. First tentative feature-points are found in each image using heuristic methods, e.g. Harris point detection, SIFT, HOG or FAST. Then tentative matches between feature points are guessed based on heuristic methods often using local image descriptors or by correlation (GCC-PHAT). Outliers are then removed using a "hypothesize and test"-paradigm (RANSAC) or by some other robust technique. This also gives initial estimates of the inverse problem. The final estimate of the parameters is obtained by non-linear optimization, e.g using non-linear least squares, robust non-linear least squares or by using some other robust metric.

Within WP 2.3 we will continue to work on robust and global optimization methods, e.g. methods for finding the global minimum to the truncated L_2 norm, L_1 minimization and globally maximal inlier sets. As has been shown in [22], such methods can be constructed using minimal solvers (from WP 3.2).

WP 3: Algebraic Geometry - Minimal problems and robust estimation of outliers

WP 3.1 General techniques for efficient solution to systems of polynomial equations

The research within algorithms for solving systems of polynomial equation is currently very active. See *e.g.* [19] and references therein for a comprehensive exposition of the state of the art in this

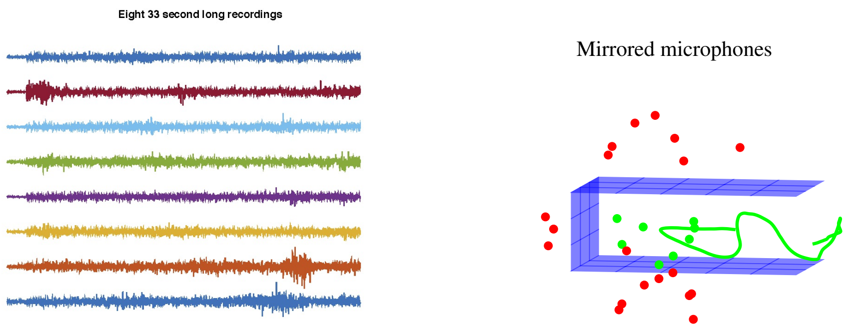

Figure 3: Results from the latest system for audio based map making. Left: Input consists of 8 sound recordings. Nothing is known about the microphone locations and sound source locations. Right: Output consists of reconstructed microphone positions (Green dots), mirrored microphone positions (red dots), sound source path (green curve) and reverberations surfaces, i.e. the floor, the ceiling and one of the walls.

field. One of the oldest methods for non-linear equation solving is the Newton-Raphson method, which is fast, but unreliable and sensitive to initialization. In several variables, resultants [21], which enables the successive elimination of variables. However, the resultant grows exponentially in the number of variables and is in most practical cases not tractable for more than two variables. A radically different approach is provided by homotopy continuation methods [39]. The main drawback of such methods is the computational complexity. At present, the best methods for geometric problems are based on eigen-decomposition of certain matrices (action matrices) representing multiplication in the quotient space $\mathbb{C}[\mathbf{x}]/I$, where I is the ideal generated by the polynomial equations. In this way we turn the problem into a numerical linear algebra problem, for which efficient and stable methods exist. The action matrix can be seen as a generalization of the companion matrix in the univariate case. The factors that make this approach attractive are that (i) it is fast and numerically feasible, (ii) it handles more than two variables, and reasonably large numbers of solutions (up to about a hundred), and (iii) it is well suited to tuning for specific applications. One major problem with this approach is finding the Gröbner basis. Even though Gröbner basis methods were mentioned in [27], these kinds of methods were to our best knowledge first used in the context of computer vision by Stewenius *et al.* [38]

The central theme here is to generalize the action matrix method, and to exploit as many previously overlooked opportunities to improve speed and stability as much as possible. The most important discovery here is arguably the large freedom in how a basis can be selected from the set of all monomials $\mathcal{M}$ occurring in an expanded set of equations. This is also where most topics still to be explored can be found. For instance, given an expanded set of equations, one would like to know if it is possible to construct a so-called solving basis for this set of equations. How should the solving basis be chosen? A solid theoretical understanding of this question and efficient and reliable algorithms for answering this for particular cases would be immensely helpful in applications. Furthermore, there is no real guidance in how to construct the expanded set of equations, except for manual testing. Currently, this is largely an empirical process done by hand. What degrees should we go to? Should we go to the same degrees for all equations and all variables? Are there any bounds on what degrees we will need to go to?

WP 3.2 Geometric understanding and solution algorithms for specific minimal problems

A key component in (i) finding initial estimates for the optimization (WP 2.1) and (ii) the global and robust optimization techniques (WP 2.3) is the understanding of the inverse problem in terms

of so-called minimal problems. With minimal problems we refer to problems with minimal amounts of data in order to solve for the parameters at least locally.
Even though the measurement equations for different modalities differ, i.e. $\lambda_{ij}\mathbf{u}_{ij} = \mathbf{P}_i\mathbf{U}_j$ for image data, $d_{ij} = |\mathbf{z}_i - \mathbf{m}_j|$ or $d_{ij} = |\mathbf{z}_i - \mathbf{m}_j| + c_i$ for distance measurements and $\mathbf{B}_{ij} = k(3\mathbf{r}_{ij}^T\mathbf{m}\mathbf{r}_{ij} - \mathbf{r}_{ij}^T\mathbf{r}_{ij}\mathbf{m})/|\mathbf{r}_{ij}|^5$ for magnetometer measurements, they can in many cases be rephrased as systems of polynomial equations. For these problems there is also a bipartite structure, e.g. receivers and senders form a bipartite graph.
These kinds of problems are typically very difficult to solve in general. As an example the problem of determining 4 receiver positions and 6 transmitter positions given all 24 distances between receivers and transmitters have been known to mathematicians within the field of rigid graphs already in 1980, cf. [10], but a solution to the embedding problem has only recently been obtained by researchers in this proposal, cf. [33].
The state-of-the-art here is that there is substantial understanding of minimal problems in vision, partial understanding of the problem for radio/audio/wifi and virtually no understanding for e.g. magnetometers. There are many interesting unsolved problems. There are also degenerate cases, *e.g.*, when all receivers are in a plane or on a line. These are important for practical applications, involve fewer measurements and merit separate investigations.

Significance

As described in the our overview of the field, efficient and numerically stable algorithms for solving key geometric problems have opened up for algorithms for (i) weeding out outliers in large datasets in computer vision, (ii) initial estimates for robust parameter estimation in, *e.g.*, map-making using optimization of non-linear least squares, truncated least squares, L1, Huber norm or other robust metric, (iii) novel algorithms for finding the global optimum with respect to the number of inliers, (iv) global optimization of over-determined problems.
Indication of significance to industry and to society at large is the recent interest in these areas by key international players such as Apple, Google, Nokia and Sony. Apple bought C3 Technologies (Swedish map-making technology using vision) and WiFiSLAM (map-making using wifi signal strength). There is also a strong interest for problems within audio, to allow better sound quality, speaker tracking and beam forming.

Preliminary results

Solving systems of Polynomial Equations: New techniques combining algebraic geometry, Gröbner basis calculation and numerical linear algebra methods have been investigated in [38]. These techniques have been refined using a combination of algebraic geometry and numerical linear algebra, [13, 16]. These new techniques have made it possible to solve problems that were infeasible before, [15, 29, 18]. In [31], it was shown how to improve speed and accuracy by optimizing over the set of multiplication monomials. In [3], it was shown how to exploit p-fold symmetries in the problem for increased speed and accuracy.
Conventional cameras: Our research on structure and motion problems and calibration for ordinary problems includes results on auto-calibration, [25, 26], structure and motion using points [24], lines [6, 8], curves, [9, 5] and surfaces [7].
TOA and TDOA problems: In [30] we study TOA and TDOA self-calibration problems in the so-called far-field approximation setting. New results were given for critical configurations for such problems. Minimal problems for structure and motion using distance measurements were studied in [38], where the minimal TOA self-calibration problem with 3 receivers and 3 senders in the plane was solved. The minimal TOA self-calibration problems in 3D (4 receivers and 6 senders

and 5 receivers and 5 senders) was recently solved in [33]. For receivers and senders that are restricted to a plane or a line a solution is given in [12]. In [11] we demonstrate that self-calibration is possible in the setting where both the transmitters and receivers are unsynchronized. In [28] we develop a nuclear-norm minimization scheme for estimating offsets for TDOA self-calibration in 3D. Near minimal solvers for TDOA self-calibration problems have also been produced. We have also characterized and solved minimal cases for TDOA self-calibration in the special case of receivers being co-linear or co-planar [2, 4]. In [32], we demonstrate how self-calibration algorithms can be used for relative localization of a single moving receiver using the signal from a signal stationary transmitter, see Figure 1. We are now pursuing the goal of automatic calibration of microphone-speaker setups using ambient sound of multiply moving sound sources. See Figure 3 for an illustration of the system that takes as input a number of sound recordings and outputs the microphone locations and the timings and positions of the moving sound sources. Recent progress in this area has made it possible to attempt at constructing systems that takes a number of audio-files as input and estimates microphone localization, sound source motion, echos and room geometry as automatic and robust as possible. This problem is in general difficult and we are currently creating state-of-the-art methods for doing this. In [36], we are the first to present such a fully automatic system that works with real data for a single moving point source in an echo-free environment. We are now constructing a system that works with real data in a normal reverbent room. Thanks to additional research on feature detection and tracking, [35], we now how an automatic system that works well as long as there is only one dominant and spatially well located sound source.

Systems and system building:

We have shown previously that we are able to take theoretical results to prototype systems and disseminate our results to industry. Examples of this within the area of systems for map-making are (i) our work on structure from motion has resulted in products (Autosurveyor, Autosurveyor II) for laser guided vehicles, commercialized by Autonavigar/Danaher Motion, (ii) we are currently in the process of developing systems that take a number of sound recordings of ambient sound and from the recordings calculate microphone positions and the positions of multiple, possible moving, sounds, see e.g.

`http://www.youtube.com/watch?v=meegLqFKxvI`

(iii) our research on large-scale bundle adjustment for images has found its way through C3 Technologies into Apple (Apple Flyover), (iii) examples of prototype systems for visual mapmaking is illustrated at

`http://www.youtube.com/watch?v=i7ierVkXYa8`

Research Team, national and international collaboration

The mathematical imaging group consists of four professors (Kalle Åström, Anders Heyden, Cristian Sminchisescu and Fredrik Kahl), four associate/assistant professors (Magnus Oskarsson, Jan Erik Solem, Niels Christian Overgaard and Carl Olsson), two post-docs and 14 PhD students.

The mathematical imaging group is part of the research project ELLIIT, which involves several research groups in Lund, Linköping, Halmstad and at BTH. Within the ELLIIT consortium we are working primarily with Professors Bo Bernhardsson and Fredrik Tufvesson at Lund University and with Professors Michael Felsberg, Alexander Kleiner and Patrick Doherty at Linköping University. Within WIFI-SLAM, we are working actively together with the company Combain Mobile AB (Björn Lindquist, Rikard Windh, Rasmus Ljungberg). Combain Mobile AB, with a background from Ericsson, Sony Ericsson, Teleca are working with development of mobile positioning solutions for e.g. Sony Mobile since 2006. Combain also offer so-called hybrid positioning solutions based primarily on cell-id to mobile phone manufacturers, freight tracking companies, operators, etc. We are also working with Sony Mobile AB (Magnus Persson) on similar research questions

(wifi and cell-id map-making and localization). Combain Mobile AB and Sony Moible AB has access to a unique database of measurements that contain GPS coordinates and signal strength measurements to 400 million wifis from 5 billion positions worldwide.
Within the analysis of sound networks we are working with Professor Andreas Jakobson at Lund University and with Sören Vang Andersen, former CTO of Skype.
At a European level we are working with the research group of Prof. Dr. Christian Schindelhauer at Uni-Freiburg, the Wireless Networks Group at Universitat Politecnica de Catalunya, and indoo.rs GmbH with time-of-arrival map-making and localization.

Commercial connections

The main applicant has the following commercial connections:
Kalle Åström is a founder of Cognimatics AB, which develops, markets and sells products for cognitive vision for mobile phones and hand-held computers, and a founder of Spiideo, which develops algorithms for recording, analysis and sharing of film clips for sport events.

References

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[2] E. Ask, S. Burgess, and K. Åström. Minimal structure and motion problems for toa and tdoa measurements with collinearity constraints. In *ICPRAM*, 2012.

[3] E. Ask, Y. Kuang, and K. Åström. Exploiting p-fold symmetries for faster polynomial equation solving. In *Proceedings of the 21st International Conference on Pattern Recognition*, 2012.

[4] E. Ask, Y. Kuang, and K. Åström. A unifying approach to minimal problems in collinear and planar tdoa sensor network self-calibration. In *European Signal Processing Conference (EUSIPCO 2014)*, 2014.

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[7] K. Åström and F. Kahl. Motion estimation in image sequences using the deformation of apparent contours. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 21(2):114–127, 1999.

[8] K. Åström, F. Kahl, A. Heyden, and R. Berthilsson. A statistical approach to structure and motion from image features. In *Interntional Workshop on Statistical Techniques in Pattern Recognition*, 1998.

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[18] M. Byröd, Z. Kukelova, K. Josephson, T. Pajdla, and K. Åström. Fast and robust numerical solutions to minimal problems for cameras with radial distortion. In *Conference on Computer Vision and Pattern Recognition*, 2008.

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[28] F. Jiang, Y. Kuang, and K. Åström. Time delay estimation for tdoa self-calibration using truncated nuclear norm. In *The 38th International Conference on Acoustics, Speech, and Signal Processing*, 2013.

[29] K. Josephson, M. Byröd, F. Kahl, and K. Åström. Image-based localization using hybrid feature correspondences. In *The second international ISPRS workshop BenCOS 2007, Towards Benchmarking Automated Calibration, Orientation, and Surface Reconstruction from Images*, 2007.

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[31] Y. Kuang and K. Åström. Numerically stable optimization of polynomial solvers for minimal pkuang-astrom-etal-iicc-13roblems. In A. Fitzgibbon, editor, *Lecture Notes in Computer Science*, volume 7574, pages 100–113. Springerm, Heidelberg, 2012.

[32] Y. Kuang, K. Åström, and F. Tufvesson. Single antenna anchor-free uwb positioning based on multipath propagation. In *IEEE International Conference on Communications*, 2013.

[33] Y. Kuang, S. Burgess, A. Torstensson, and K. Åström. A complete characterization and solution to the microphone position self-calibration problem. In *The 38th International Conference on Acoustics, Speech, and Signal Processing*, 2013.

[34] C. Olsson and O. Enqvist. Stable structure from motion for unordered image collections. In *SCIA 2011*, 2011.

[35] S. Segerblom Rex. Robust time difference estimation for unknown microphone positions with reverberation. Master's thesis, Centre for Mathematical Sciences LTH, Lund University, Sweden, 2015.

[36] Z. Simayijiang, F. Andersson, Y. Kuang, and K. Åström. An automatic system for microphone self-localization using ambient sound. In *European Signal Processing Conference (Eusipco 2014)*, 2014.

[37] N. Snavely, S. M. Seitz, and R. Szeliski. Modeling the world from Internet photo collections. *Int. Journal of Computer Vision*, 80(2):189–210, 2008.

[38] H. Stewénius. *Gröbner Basis Methods for Minimal Problems in Computer Vision*. PhD thesis, Lund University, Apr. 2005.

[39] J. Verschelde. Phcpack: A general-purpose solver for polynomial systems by homotopy continuation. *ACM Transactions on Mathematical Software*, 25(2):251–276, 1999.

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

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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	Karl Åström	25
2	Other personnel without doctoral degree	Ny doktorand	100

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Karl Åström	25	317,000	327,000	336,000	347,000	1,327,000
2	Other personnel without doctoral degree	Doktorand	100	489,000	504,000	519,000	535,000	2,047,000
	Total			806,000	831,000	855,000	882,000	3,374,000

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 o lab	40,000	40,000	40,000	40,000	160,000
	Total	40,000	40,000	40,000	40,000	160,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Utrustning	Kameror, mikrofoner m m	30,000	30,000	30,000	30,000	120,000
2	Resor	Konferenser	30,000	30,000	30,000	30,000	120,000
	Total		60,000	60,000	60,000	60,000	240,000

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	806,000	831,000	855,000	882,000	3,374,000		3,374,000
Running costs	60,000	60,000	60,000	60,000	240,000		240,000
Depreciation costs					0		0
Premises	40,000	40,000	40,000	40,000	160,000		160,000
Subtotal	906,000	931,000	955,000	982,000	3,774,000	0	3,774,000
Indirect costs	363,000	374,000	385,000	396,000	1,518,000		1,518,000
Total project cost	1,269,000	1,305,000	1,340,000	1,378,000	5,292,000	0	5,292,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

The project concerns new mathematics and methods for map-making, localization and navigation. The project is intended to financially support one phd student and part time for the main applicant. In the project we will work closely together with several other researchers, both nationally and internationally, whose research time will not be covered by this project. Furthermore we apply for some funding for purchase of experimental equipment, such as microphones, sound cards, cables, low energy bluetooth beacons, etc. We also apply for funding for travel for the PhD stu

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	Total
1	MAPCI	Karl Åström			600,000	600,000	0	0	1,200,000
	Total				600,000	600,000	0	0	1,200,000

CV and publications

CV

B: CV Kalle Åström

Professor Kalle Åström
Home address: Planvägen 13, 226 47 Lund, Tel: 046 - 12 14 11.

1. Undergraduate
Bachelor of Science in mathematics, January 31 1990
Master of Science Engineering Physics, August 31 1991, grade point average 5.0 (maximum is 5.0). Masters thesis: 'Where am I and what am I seeing? Algorithms for a Laser Guided Vehicle'.)
2. PhD 1996, Dept of mathematics, Engineering faculty, Lund University, 'Invariancy Methods for Points, Curves and Surfaces in Computational Vision'. Supervisor Gunnar Sparr.
4. Docent degree Dept of mathematics, Engineering faculty, Lund University,1999.
5. Current employment LTH Professor and deputy head of department, Centre for Mathematical Sciences, Lund University, 020201 to present. I am currently working 50% with research, 30% with teaching and 20% as deputy head of department. Most of the research is funded by external grants.
6. Previous employments
LTH Professor at the Centre for Mathematical Sciences, Lund University,020201. In the period 2002-2008 I worked roughly 60% research and 40% teaching. Since february 2008 I have worked 50% as head of division.
LTH Research and development, Decuma AB, 000401 to 020630. 20% research and development.
LTH Associate professor at the Centre for Mathematical Sciences, Lund University,000115 to 011231. 80% research and teaching.
LTH Lecturer at the department of mathematics Lund University, 990501 to 990930.
LTH Post doctoral fellow at the department of mathematics Lund University, 961001 to 990430. The position includes 75% research and 25% teaching.
LTH PhD student position 920101-960930 (67% research studies and 33% teaching).
7. Paternal leave
Love Paternal leave 050901-051231 (100%).
Sofia Paternal leave 010901-011031 (50%) and 011101-020131 (100%).
Oskar Paternal leave 991001-000115 (100%).
8. Supervised PhD theses as main supervisor
Johansson, B. Computer Vision using Rich Features - Geometry and Systems, 2002,
Oskarsson, M. Solutions and their Ambiguities for Structure and Motion Problems, 2002,
Stewénius, H. Gröbner Basis Methods for Minimal Problems in Computer Vision, 2005,
Ericsson, A. Automatic Shape Modelling with Applications in Medical Imaging, 2006.
Eriksson, A. Optimization Methods for Large Scale Combinatorial Problems and Bijectivity Constrained Image Deformations, 2008.
Sternby, J. Template Based Recognition of On-Line Handwriting, 2008.
Karlsson, J. Towards Fully Automatic Optimal Shape Modeling, 2008.
Ardö, H. Multi-target Tracking Using on-line Viterbi Optimisation and Stochastic Modelling, 2009.
Byröd, M. Numerical Methods for Geometric Vision: From Minimal to Large Scale Problems, 2010.

Kuang, Y. Polynomial Solvers for Geometric Problems - Applications in Computer Vision and Sensor Networks, 2014.
Ask, E. Polynomial Solvers for Geometric Problems - Applications in Computer Vision and Sensor Networks, 2014.
Supervised PhD students as co-supervisor
Olof Barr, 2007, Johan Lindström 2008, Carl Olsson, 2009, Olof Enquist, 2013, Sebastian Haner, 2015.
Supervised postdocs
Ardö, H., 2008-2012. Byröd, M., 2010-2011. Nilsson, M., 2012-2013.
9. Other
Professional activities
Deputy head of department, Centre for Mathematical Sciences, 2014-
Head of division, mathematics (engineering faculty) and numerical analysis (engineering and scince faculty) of the Centre for Mathematical Sciences, 2008-2014.
Member of forskningsnämnd 1' at LTH, 2009-2015
Chairman of the research senate at LTH 2007-2008.
Member of the research board 'forskningsberedningen' of LTH 2006-2009.
Member of STFI-Packforsk scientific advisory board, 2004-2005.
Cofounder and chairman of the Board of the company Cognimatics AB (algorithms for cognitive vision in handheld computers and mobile phones), 2003-
Cofounder and member of the Board of the company Decuma AB (algorithms for hand writing recognition), 1999-2004.
Cofounder of the company Spiideo AB (analysis of sport recordings), 2012-.
Member of the Board of Lund Institute of Technology, 2000-2002.
President of the Swedish Society for Automated Image Analysis, 1998-2002.
Member of the governing board of the IAPR, 1998-2004.
Papers in journals: 30.
Book chapters: 4.
Refereed conference contributions: 107.
Other conference contributions: 24.
Examiner at PhD dissertations: 4.
Examiner at licentiate theses: 5.
Programme committee member at SMIP, ICCV, ECCV, CVPR, ICPR, SCIA,
Reviewer for IEEE PAMI, IJCV, CVIU, JMIV.
Organizer of Swedish Symposium on Image Analysis 1996, 2002, 2008.
Google Scholar: 2282 citations, h-index: 24.
Co-author of about 9 patent applications resulting in 5 granted patents within medical image processing (Exini Diagnostics), smart devices (C-tech/Anoto), radar measurements (Airborne Hydrography), laser guided navigation (NDC/Danaher Motion) handwriting recognition (Decuma). Co-founder of three spin-off companies: Decuma AB, Cognimatics AB and Spiideo AB.
Rewards
Cognimatics AB (which I co-founded in 2003) got the Rapidus 'company of the year' award in 2011 and Deloitte Technology Fast 500 EMEA award in 2010, 2011 and 2012
Cognimatics AB (which I co-founded in 2003) got one of the Vinn Nu awards 2003.
Decuma AB (which I co-founded in 1999) got the EU IST Grand Prize award 2003.

Nordic Award for the best PhD Thesis in Pattern Recognition 1995-1996, presented at the Scandinavian Conference for Image Analysis in Lappenranta 1997.
First place in Innovation Cup 1991, a national competition for innovative ideas, for the development of a laser positioning system for a self guided vehicle.

Publication list

Appendix C: List of publications 2007- (Kalle Åström)

Publication list extracted from Mathematical Imaging Group
`http://www.maths.lth.se/vision/publications/`.
Number of citations from Google Scholar.
`http://scholar.google.se/citations`user=YIzs6eoAAAAJ&hl=en?
Publication summary:
Refereed journal and conference publications: 137.

Citation summary:
Citations: 2477.
h-index: 25.
i10-index: 58.

Top five citations: 260, 223, 99, 95, 80.

[T1] Heyden, Anders and Åström, Kalle, "Euclidean Reconstruction from Image Sequences with Varying and Unknown Focal Length and Principal Point,"*Proceedings Conference on Computer Vision and Pattern Recognition*, pp. 438–443, 1997. Citation count: 260.

[T2] Heyden, A. and Åström, K., "Euclidean Reconstruction from Constant Intrinsic Parameters,"*International Conference on Pattern Recognition*, pp. 339–343, 1996. Citation count: 223.

[T3] Cipolla, Roberto and Åström, Kalle and Giblin, Peter, "Motion from the Frontier of Curved Surfaces,"*Procedings of the Fifth International Conference on Computer Vision (ICCV 95),*, pp. 269-276, 1995. Citation count: 99.

[T4] Aanaes, H and Fisker, R and Åström, K and Carstensen, J. M., "Robust Factorization,"*IEEE transactions on Pattern Analysis and Machine Intelligence*, vol. 24, no. 9, pp. 1215–1225, 2002. Citation count: 95.

[T5] Kahl, Fredrik and Triggs, Bill and Åström, Kalle, "Critical Motions for Auto-Calibration When Some Intrinsic Parameters Can Vary,"*Journal of Mathematical Imaging and Vision*, vol. 13, no. 2, pp. 131–146, 2000. Citation count: 80.

1. Journal Papers

[J1] Burgess, Simon and Kuang, Yubin and Åström, Kalle, "TOA sensor network self-calibration for receiver and transmitter spaces with difference in dimension,"*Signal Processing*, vol. 107, pp. 33–42, 2015.

[J2] Enqvist, Olof and Ask, Erik and Kahl, Fredrik and Åström, Kalle, "Tractable Algorithms for Robust Model Estimation,"*International Journal of Computer Vision*, 2014.

[J3] Ardö, Håkan and Åström, Kalle, "Bayesian Formulation of Image Patch Matching Using Cross-correlation,"*Journal of Mathematical Imaging and Vision*, vol. 43, no. 1, pp. 72–87, 2012. Citation count: 5.

[J4] Enqvist, Olof and Kahl, Fredrik and Olsson, Carl and Åström, Kalle, "Global Optimization for One-Dimensional Structure and Motion Problems,"*SIAM Journal of Imaging Science*, vol. 3, no. 4, 2010. Citation count: 1.

[J5] Byröd, Martin and Josephson, Klas and Åström, Kalle, "Fast and Stable Polynomial Equation Solving and Its Application to Computer Vision,"*International Journal of Computer Vision*, vol. 84, no. 3, pp. 237–, 2009. Citation count: 41.

[J6] Laureshyn, Aliaksei and Åström, Kalle and Brundell-Freij, Karin, "From speed profile data to analysis of behaviour: classification by pattern recognition techniques,"*IATSS Research*, vol. 33, no. 2, pp. 88–98, 2009. Citation count: 6.

[J7] Kukelova, Zuzana and Byröd, Martin and Josephson, Klas and Pajdla, Tomas and Åström, Kalle, "Fast and Robust Numerical Solutions to Minimal Problems for Cameras with Radial Distortion,"*Computer Vision and Image Understanding*, 2008. Citation count: 16.

2. Conference papers with peer-review

[C1] Jiang, Fangyuan and Kuang, Yubin and Solem, Jan Erik and Åström, Kalle, "A Minimal Solution to Relative Pose with Unknown Focal Length and Radial Distortion,"*The 12th Asian Conference on Computer Vision*, 2014.

[C2] Saunier, Nicolas and Ardö, Håkan and Jodoin, Jean-Philippe and Laureshyn, Aliaksei and Nilsson, Mikael and Svensson, Åse and Miranda-Moreno, Luis and Bilodeau, Guillaume-Alexandre and Åström, Kalle, "A Public Video Dataset for Road Transportation Applications,"*2014 TRB Annual Meeting Workshop on Comparison of Surrogate Measures of Safety Extracted from Video Data*, 2014. Citation count: 1.

[C3] Ask, Erik and Kuang, Yubin and Åström, Kalle, "A Unifying Approach to Minimal Problems in Collinear and Planar TDOA Sensor Network Self-Calibration,"*European Signal Processing Conference (EUSIPCO 2014)*, 2014.

[C4] Simayijiang, Zhayida and Andersson, Fredrik and Kuang, Yubin and Åström, Kalle, "An Automatic System for Microphone Self-Localization Using Ambient Sound,"*European Signal Processing Conference (Eusipco 2014)*, 2014.

[C5] Medved, Dennis and Jiang, Fangyuan and Exner, Peter and Oskarsson, Magnus and Nugues, Pierre and Åström, Kalle, "Combining Text Semantics and Image Geometry to Improve Scene Interpretation,"*International Conference on Pattern Recognition Applications and Methods*, 2014. Citation count: 2.

[C6] Tegen, Agnes and Weegar, Rebecka and Hammarlund, Linus and Oskarsson, Magnus and Jiang, Fangyuan and Medved, Dennis and Nugues, Pierre and Åström, Kalle, "Image Segmentation and Labeling Using Free-form Semantic Annotation,"*International Conference on Pattern Recognition*, 2014. Citation count: 1.

[C7] Nilsson, Mikael and Ardö, Håkan and Åström, Kalle and Herlin, Anders and Bergsten, Christer and Guzhva, Oleksiy, "Learning Based Image Segmentation of Pigs in a Pen,"*Visual observation and analysis of Vertebrate And Insect Behavior 2014*, 2014.

[C8] Zhayida, Simayijiang and Burgess, Simon and Kuang, Yubin and Åström, Kalle, "Minimal Solutions for Dual Microphone Rig Self-Calibration,"*European Signal Processing Conference (EUSIPCO 2014)*, 2014.

[C9] Kuang, Yubin and Solem, Jan Erik and Kahl, Fredrik and Åström, Kalle, "Minimal Solvers for Relative Pose with a Single Unknown Radial Distortion,"*IEEE Conference on Computer Vision and Pattern Recognition*, 2014. Citation count: 1.

[C10] Burgess, Simon and Kuang, Yubin and Wendeberg, Johannes and Åström, Kalle and Schindelhauer, Christian, "Minimal Solvers for Unsynchronized TDOA Sensor Network Calibration,"*Lecture Notes in Computer Science*, pp. 95–110, 2014.

[C11] Kuang, Yubin and Zheng, Yinqiang and Åström, Kalle, "Partial Symmetry in Polynomial Systems and Its Application in Computer Vision,"*IEEE Conference on Computer Vision and Pattern Recognition*, 2014.

[C12] Oskarsson, Magnus and Åström, Kalle and Torstensson, Anna, "Prime Rigid Graphs and Multidimensional Scaling with Missing Data,"*International Conference on Pattern Recognition*, 2014.

[C13] Palmér, Tobias and Åström, Kalle and Enqvist, Olof and Ivica, Nela and Petersson, Per, "Rat Paw Tracking for Detailed Motion Analysis,"*Visual observation and analysis of Vertebrate And Insect Behavior 2014*, 2014.

[C14] Kuang, Yubin and Oskarsson, Magnus and Åström, Kalle, "Revisiting Trifocal Tensor Estimation using Lines,"*International Conference on Pattern Recognition*, 2014.

[C15] Kjellberg, Tobias and Oskarsson, Magnus and Palmér, Tobias and Åström, Kalle, "Tracking the Motion of Box Jellyfish,"*Visual observation and analysis of Vertebrate And Insect Behavior 2014*, 2014.

[C16] Weegar, Rebecka and Hammarlund, Linus and Tegen, Agnes and Oskarsson, Magnus and Åström, Kalle and Nugues, Pierre, "Visual Entity Linking: A Preliminary Study,"*Cognitive Computing for Augmented Human Intelligence: Papers from the AAAI-14 Workshop*, 2014.

[C17] Kuang, Yubin and Burgess, Simon and Torstensson, Anna and Åström, Kalle, "A Complete Characterization and Solution to the Microphone Position Self-Calibration Problem,"*The 38th International Conference on Acoustics, Speech, and Signal Processing*, 2013. Citation count: 16.

[C18] Simayijiang, Zhayida and Backman, Sofia and Ulén, Johannes and Wikström, Sverre and Åström, Kalle, "Exploratory study of EEG burst characteristics in preterm infants,"*35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 4295–4298, 2013.

[C19] Jiang, Fangyuan and Enqvist, Olof and Kahl, Fredrik and Åström, Kalle, "Improved Object Detection and Pose Using Part-Based Models,"*Scandinavian Conference on Image Analysis*, 2013.

[C20] Burgess, Simon and Kuang, Yubin and Wendeberg, Johannes and Åström, Kalle and Schinelhauer, Christian, "Minimal Solvers for Unsynchronized TDOA Sensor Network Calibration using Far Field Approximation,"*9th International Symposium on Algo-*

rithms and Experiments for Sensor Systems, Wireless Networks and Distributed Robotics, 2013. Citation count: 1.

[C21] Ask, Erik and Burgess, Simon and Åström, Kalle, "Minimal Structure and Motion Problems for TOA and TDOA Measurements with Collinearity Constraints,"*Proceedings of the 2nd International Conference on Pattern Recognition Applications*, pp. 425–429, 2013. Citation count: 4.

[C22] Kuang, Yubin and Åström, Kalle, "Pose Estimation with Unknown Focal Length using Points, Directions and Lines,"*Proceedings of IEEE International Conference on Computer Vision (ICCV2013)*, pp. 529–536, 2013. Citation count: 1.

[C23] Zheng, Yinqiang and Kuang, Yubin and Sugimoto, Shigeki and Åström, Kalle and Okutomi, Masatoshi, "Revisiting the PnP Problem: A Fast, General and Optimal Solution,"*Proceedings of IEEE International Conference on Computer Vision, ICCV2013*, pp. 2344-2351, 2013. Citation count: 11.

[C24] Kuang, Yubin and Åström, Kalle and Tufvesson, Fredrik, "Single Antenna Anchor-Free UWB Positioning based on Multipath Propagation,"*IEEE International Conference on Communications*, 2013. Citation count: 3.

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[C26] Jiang, Fangyuan and Kuang, Yubin and Åström, Kalle, "Time Delay Estimation for TDOA Self-Calibration using Truncated Nuclear Norm,"*The 38th International Conference on Acoustics, Speech, and Signal Processing*, 2013. Citation count: 9.

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6. Patents

CV

Name: Karl Åström	**Doctorial degree:** 1996-05-30
Birthdate: 19670218	**Academic title:** Professor
Gender: Male	**Employer:** Lunds universitet

Research education

Dissertation title (swe)

Dissertation title (en)

‘Invariancy Methods for Points, Curves and Surfaces in Computational Vision

Organisation	Unit	Supervisor
Lunds universitet, Sweden Sweden - Higher education Institutes	107151 Matematik LTH	Gunnar Sparr

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
10102. Geometri		1996-05-30

Publications

Name: Karl Åström	**Doctorial degree:** 1996-05-30
Birthdate: 19670218	**Academic title:** Professor
Gender: Male	**Employer:** Lunds universitet

Åström, Karl 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.