Application

2015-03-31

2015-04969	Enqvist, Olof	NT-14

Information about applicant

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Project site: 3202 - Signalbehandling och medicinsk teknik

Information about application

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Funds applied for

Year:	2016	2017	2018	2019
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Descriptive data

Project info

Project title (Swedish)*

Särdragsbaserade metoder för datorseende och medicinsk bildanalys

Project title (English)*

Improved Feature-Based Methods for Computer Vision and Medical Imaging

Abstract (English)*

One of the biggest success stories in modern computer vision is the development of robust feature descriptors for 2D images. It has made an immense impact on the field and improved the state-of-the-art for a number of classical applications. The main objective of this research project is to further improve feature-based methods by more careful mathematical modelling and to adapt the underlying models to other settings where computationally more demanding and less reliable alternatives prevail. In particular, we will focus on 3D imaging sensors - both medical devices such as MR and CT and depth cameras.

Popular scientific description (Swedish)*

Särdragsbaserade metoder för datorseende och medicinsk bildanalys

Kameror och andra bildsensorer används alltmer både i industrin och på våra sjukhus. Klassiska kameror används i en mängd tillämpningar, t.ex. för bildsökning på internet, inom robotnavigering samt för att skapa tredimensionella modeller av byggnader eller hela städer. Medicinska bildtekniker som magnetisk resonanstomografi (MR), datortomografi (CT) och ultraljud skapar en tredimensionell bild av människokroppen och ger helt unika möjligheter för att diagnostisera och förstå sjukdomar.

I takt med att antalet tillämpningar ökar så ökar också behovet att tillförlitliga analysverktyg. Inte minst när personer med begränsad teknisk utbildning ska använda sig av verktygen som inom medicin eller när mängden data kräver en helautomatiserad analys som i bild-sök eller konstruktion av 3D-modeller.

Ett av de största framstegen i datorseende är att utvecklingen av robusta metoder baserade på intressepunkter och deskriptorer. Basen för dessa metoder är att man istället för att beskriva bilden i sin helhet väljer ut ett antal intressepunkter. För varje intressepunkt används en så kallad deskriptor för att beskriva bilden i en liten omgivning av punkten. Deskriptorn är helt enkelt en vektor med hundratalet tal som beskriver bildens utseende. Genom att jämföra deskriptor-vektorer för intressepunkter från olika bilder kan man hitta hitta punkter med liknande utseende. En stor fördel är att eftersom varje deskriptor bara beskriver en liten del av bilden så är dessa metoder mycket robusta mot förändringar i bilden och generaliserar mycket bra till nya tillämpningar. Detta är nyckelegenskaper för analysverktyg som ska tas i praktisk användning.

Trots det har denna klass av metoder inte en dominerande ställning när det gäller tredimensionella bilder, vare sig det gäller medicinska bilder som magnetröntgen och datortomografi eller djupsensorer som Microsofts Kinect-sensor. Vi tror att det finns flera orsaker, till exempel att metoder baserade på intressepunkter inte har anpassats för dessa tillämpningar samt att noggrann matematisk modellering saknas. I detta förslag kommer vi därför att studera de underliggande matematiska principerna för denna typ av metoder och utveckla ny teori och algoritmer med fokus på tredimensionella bilder såsom MR, CT och djup-kameror.

Project period

Number of project years*

4

Calculated project time*

2016-01-01 - 2019-12-31

Deductible time

Deductible time

Cause	Months

Career age: 46

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*

2. Teknik > 206. Medicinteknik > 20603. Medicinsk bildbehandling

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

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

Keyword 1*

computer vision

Keyword 2*

local features

Keyword 3*

medical image analysis

Keyword 4

Keyword 5

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 kommer en del medicinska bilder att hanteras, men dessa är alltid anonymiserade.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

Improved Feature-Based Methods for Computer Vision and Medical Imaging

1 Purpose and aims

One of the real success stories in computer vision is the development of estimation techniques based on local features such as SIFT and SURF [12, 3]. Originating in scale-space and invariance theory [10], it has made an immense impact on the field and improved state of the art for a number of classical vision applications, including object recognition, image search, structure from motion and simultaneous localization and mapping. In recent years, the focus has largely been moving to dense estimation methods working with the image as a whole [18]. To some extent this has caused the development of sparse features to slow down. This is unfortunate, as the feature-based methods are still important both in their own right, but not least to initialize the heavier machinery of dense estimation. The reason is that dense methods, although offering a more correct model, typically lead to very demanding optimization problems that only allow for local optimization.

The purpose of this project is to advance state of the art for feature-based methods, both by improving the feature detectors and descriptors themselves and by improving feature-based model fitting. A particular aim is to improve the performance of feature-based methods in applications where they are currently not that well used, such as medical imaging and depth sensors.

Theoretical goals.

- Studying the effect of model error due to simplified models, in typical estimation problems in computer vision and medical imaging.
- Studying the robustness of different loss functions, hierarchical methods and developing new theoretically founded approaches which are robust to model error.
- Adapting feature detectors and descriptors to images with poor texture and high noise level, such as many medical modalities
- Developing mathematical models to handle repetetive structures and ambiguities.

Application goals.

- Creating simple methods for 3D reconstruction which are robust to model error.
- Creating off-the-shelf feature-based tools for medical images.

2 Survey of the field

Features in computer vision and medical imaging. There has been a lot of research on feature-based estimation, developing features that are invariant to scale, rotation and lighting conditions [12, 3]. These descriptors have also been generalized to n-dimensional images and used in the medical domain [4]. However, it is hard to motivate scale invariance in 3D images as the scale is typically known. In most applications, the same statement is true for rotation invariance as well. Moreover, the detectors are tuned to small scales (little spatial support) in order to be robust to the occlusion

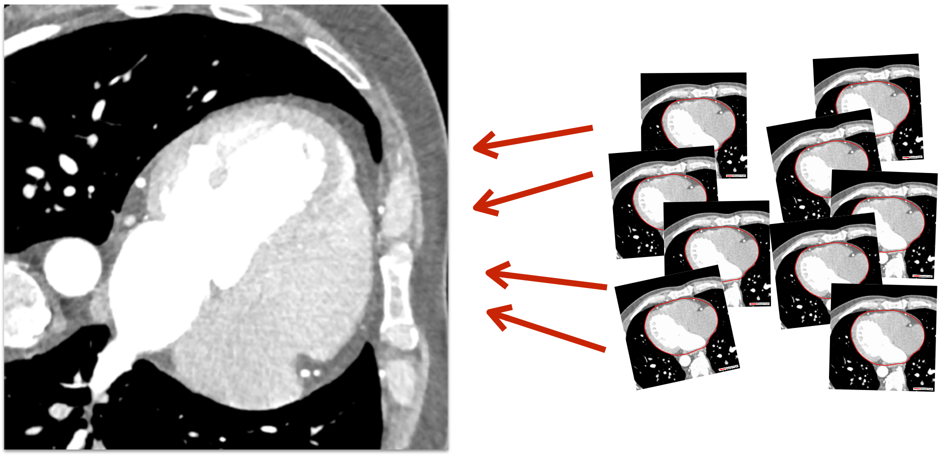

Figure 1: Image segmentation using atlases. Each atlas image is first registered to the new image, and then the labels of the atlas are transferred and used for classification.

problem in the 2D setting. This problem is not relevant for 3D images. In summary, significant discriminating power of feature descriptors may be lost due to incorrect modelling.

In conjunction with feature descriptors, robust techniques for model estimation have been developed based on the type of point-to-point correspondences obtained from such descriptors, see [5, 6] and the references therein. This is especially true for 3D reconstruction problems where there are innumerable publications on diverse aspects such as optimal estimation, large-scale estimation and methods that work in real-time, see [8, 1, 7]. Despite the extensive literature, we believe that there is still room for improving the feature-based methods and adapting them to new settings.

Image registration. There are several standard registration tools available, see the recent survey [17]. The most popular methods/tools are dominantly based on loss functions that integrate the deviations over the whole image domain between the transformed source and target images, so-called intensity-based methods. This is true both for the high-dimensional models of non-rigid registration and for low-dimensional models with transformation groups, like rigid, affine and similarity transformations. Local optimization techniques are applied to obtain a solution, and as the loss functions are commonly non-convex, this approach is plagued by the local minima problem. Another problem is that the loss functions in general are not robust which make them sensible to outliers structures. There are a few alternatives which have more sophisticated error models, for example, Huber-like loss functions [15]. Still, the dependence on a good initialization remains due to the non-convexity of the loss function. There are also feature-based registration methods that only rely on geometrically defined interest points, often targeted for a particular application, for instance, thoracic CT registration [13]. The winner of the EMPIRE10 grand challenge [13] used feature-constrained registration, however, the method is not able to cope with any false matches.

Multi-atlas segmentation. In many segmentation tasks, the best performing methods are based on label propagation which first registers expert-segmented images (*atlases*) to a target image, and then directly transfers labels from the atlases to the target image, cf. Fig. 1. Conflicting labels are combined with a voting scheme [19][1]. For brain MRI segmentation, atlas-based segmentation is the method of preference, but other settings, for example, pericardium segmentation [16] have also been tested. A direct application of the basic principle to more general settings with more anatomical variations is

[1] Winner of MICCAI 2012 “Challenge on Multi-Atlas Labeling”.

hindered due to the following reasons. First, the image registration problem can be hard to solve accurately, which is a prerequisite. Current methods for registration do not in general handle large shape changes or abnormalities [17], and those that do, for example, [15] are dependent on a good initialization. Second, in order to achieve accurate registration results, to our knowledge all atlas methods use intensity-based registration which is inherently slow and hence limits the applicability to small size atlases.

3D reconstruction from depth sensors. The use of depth sensors has been popularized thanks to the availability of cheap, consumer sensors. The original work of KinectFusion [14] showed that one can compute both dense surfaces and the camera motion from a stream of depth images. This work and subsequent approaches to the same problem all use the whole image to compute the camera trajectory [18]. Similar to the registration problem, a good initialization is needed for the camera pose of each time frame, which can be obtained from the previous frame by assuming a small camera movement. More serious problems arise when performing loop-closing or when the camera has lost its track. Such problems can be remedied with feature-based methods that are not dependent on initialization. Recent work has focused on how to calibrate a depth sensor [20]. However, there is still no widely accepted and physically valid camera model, so the error modelling remains an open problem.

3 Program description

Work package 1: Feature-Based Model Fitting

We aim to develop mathematical models of model errors produced by simplified models during image registration and structure-from-motion estimation.

Model estimation is challenging, because it demands not only numerical parameter estimation, but also selection of model structure. Let us consider the registration of two point sets as an example. If we assume that the point sets are related by a rigid transformation, then we have decided the overall model structure. Any deviations from a rigid transformation is noise. A very common assumption is that the noise on *correct point correspondences* is Gaussian. At the same time, there are also completely random measurements, outliers, that should be ignored.

Based on these assumptions we can seek statistically favorable model parameters and much research has been focused on efficient methods for this objective. In general, using simple models with only a few parameters yields a simple estimation problem that enables rigorous handling of outliers and limits the risk of overfitting. Hence simple approximate models are often chosen over more complex high-fidelity models. An illustrating example comes from estimating the epipolar geometry from two views. That is, estimating the relative pose of two cameras with a semi-calibrated camera model (only the focal length is unknown) often produces better results than using a full projective camera model. The problem is estimating parameters such as the principal point of the camera with a limited number of measurements often produces poorer results than assuming them to be their typical value (*e.g.*, principal point is usually at the center of the image) [8].

An aspect that is often overlooked is how simplifications in the model structure affects noise assumptions and the resulting parameter estimates. Often a simplified model is used and the noise (on correct measurements) is assumed to be independent and Gaussian. This risks deeming a portion of the correct measurements as outliers, while fitting a model only to a subset of data. One aim of this project is to carefully model the effect that incorrect or simplified model assumptions have on the end result and to develop new methods that are robust to this type of errors.

These ideas are inspired by the model error estimation in the theory of system identification [11]. Just as in that scenario, it is not fruitful to model the distribution of the error residuals of the simplified model with a very precise model. Then we might as well improve the system model. The modelling of the model errors must be done at a much coarser level. For example, one can investigate the dependence of the errors with respect to spatial location in the image. It will often be true that the noise on features in the same part of the image is highly dependent and naturally this should affect the way we perform parameter estimation.

Task 1.1: Image registration. One important application where this type of modelling is highly relevant is in registering medical images such as CT or MR. With whole-body images from different subjects, there are non-rigid deformations that fit very poorly with the assumption of Gaussian independent noise. Standard fitting techniques based on least squares or truncated least squares risk fitting a model to only a part of the data. The tools needed will be a mixture of analytical tools and empirical observations on real data.

Goal: Develop mathematical models of model errors for simplified image registration models and corresponding optimization methods for parameter estimation.

Task 1.2: Structure from motion estimation. One case that can benefit from a more detailed analysis of model error is the structure from motion problem, that is, the problem of estimating the 3D structure of a scene from multiple images of that scene. This problem is normally solved in multiple steps. The first step consists of estimating the geometry of two selected views. Often a very simple camera model is used to enable estimation that is robust against outliers and avoid overfitting. More complex phenomena such as lens distortion, rolling shutter or deformable scenes are ignored. But these simplifications may mean problems on a larger scale. Systematic errors introduced by the simplified local models can lead to problems with loop-closing. One approach to deal with this is to use hierarchical models, but a rigorous analysis of the problems introduced by using simplified models and how to structure the parameter estimation to minimize these problems is still missing. We will investigate this phenomenon both for standard 2D images using semi-calibrated camera models and for 3D sensors such as KINECT.

Goal: Develop mathematical models of model errors for simplified camera models, both for 2D images and 3D depth sensors and corresponding optimization methods for parameter estimation.

Work package 2: Feature Detectors and Descriptors

Feature-based methods have been very successful in computer vision for 2D imagery, thanks to ground-breaking methods like SIFT and SURF [12, 3]. They are often used for building large-scale 3D models from 2D images [1, 7] as well as for computing detailed dense surfaces from stereo cameras. For many computer vision tasks they work as off-the-shelf solutions that can be used without detailed understanding of the underlying method. The relatively low dimension of feature-based estimation problems permits the use of global optimization methods that find a good solution regardless of initialization and even with high rates of outliers and noise [6].

An aim of this research project is to make full use of these advantages in automated analysis of 3D images, either obtained from sensors like CT or MR, or depth sensors like KINECT. The expectation is that this will create robust tools for some key problems in 3D computer vision and medical image analysis - tools that can be used not only by other researchers but also by, for example, medical personnel without technical training. Application-wise the focus lies on camera pose estimation and image registration, especially in the multi-atlas setting, where it has already been shown that efficient and accurate registration also provides a state-of-the-art tool for image segmentation.

Task 2.1: Feature modelling and matching. One aim of this project is to develop new methods for feature extraction, which are more suitable for 3D image modalities such as CT and MR. One important aspect is that this type of images tend to have less local texture information and more noise. On the other hand, the imaging process is normally more restricted leading to a smaller need for invariance. For classical computer vision — working with 2D images of the 3D world — it has been essential to achieve invariance to scaling and rotations. But for 3D modalities such as CT, MR, PET or depth sensors this type of invariance is not necessarily desirable. For example, rather than requiring scale invarance, we will explore how the scale information can be used to improve feature performance. Larger scales are good for initial feature matching as the risk of ambiguity is smaller, but using too large a scale reduces robustness against outlier structures. Finer scales are important to accurately localize important structures, but they more sensitive to noise.

Another challenge that has not been relevant for the development of feature descriptors in computer vision is the aspect of different imaging modalities. A major challenge in making feature-based registration an off-the-shelf tool in medical image analysis lies in developing features that are capable of matching between different modalities. State of the art in these modes are block-based matching based on mutual information, but this technique is computationally very costly and requires high-quality initialization, which limits the practical utility of the method. An aim of the project is to adapt feature descriptors to 3D images by developing theory for scale selection and inter-modality matching.

Goal: To develop frameworks for scale selection for 3D descriptors and inter-modality matching.

Task 2.2: Feature modelling for multi-atlas segmentation. In this part, we are interested in how to build models of feature sets to use in multi-atlas segmentation rather than individual feature points. Particular attention will be given to aspects of efficiency and model stability.

Segmentation based on multi-atlases has achieved state-of-the-art results for many challenging segmentation problems and a lot of evidence suggests that the results could be further improved if the number of atlas images could be increased. There are two challenging problems. Firstly, manual segmentation of high-resolution 3D images is a very time-consuming and laborious process. The second problem is that the current registration methods are computationally expensive — typically in the order of several minutes on a standard PC for registering two CT images — and therefore recording of a new image to a set of atlas images is indeed very costly. It is one of the major bottlenecks for the usage of large-scale atlases.

In preliminary work, we have shown that feature-based registration can be used to speed up and robustify registration in a multi-atlas setting, see Section 5. But much more can be gained by more careful modelling of the set of atlases. Co-registering all atlas images allows us to create an average atlas image and model the distribution of individual features—both spatially and in descriptor space. This makes it easier to find correct correspondences and features with a large spatial variation can be given a lower weight.

Given a new image that we want to analyze, we first register to the average atlas image. This implicitly defines correct feature correspondences to all the individual atlas images while discarding incorrect correspondences. In terms of efficiency, the most expensive step of feature-based registration is to handle outlier correspondences, so using an average atlas will significantly reduce the computational cost and achieve an extremely fast and reliable registration method.

To further improve the segmentation result, existing methods use non-rigid registration to accurately align structures between the new image and the atlas image. In non-rigid registration a high-dimensional global deformation field is computed at great computational cost. We believe that similar performance can be achieved by local modelling of the targeted structures. Using the atlas images, one can automatically determine which features have a stable position relative to the target structure and use these to estimate the exact segmentation border in a new image. A great advantage is the efficiency as we avoid the expensive non-rigid registration and as the local models can estimated in parallel.

Goal: Develop a framework for modelling feature-based atlases and corresponding optimization methods for atlas construction and registration.

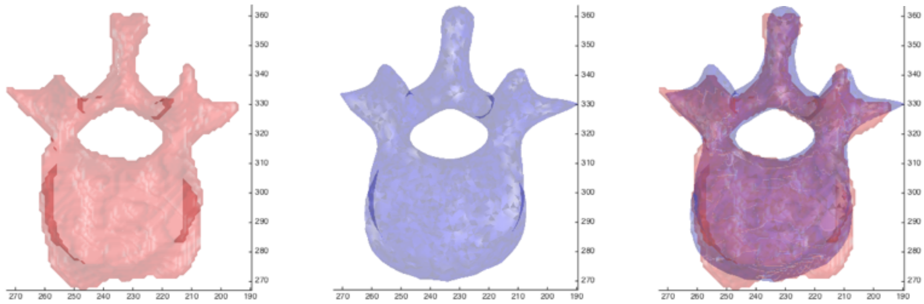

Figure 2: On the left we see a segmentation of vertebra obtained manually by an expert. In the middle we see a fully automatic feature-based segmentation and to the right an overlay of the two segmentations. Currently, the process risk failing due to finding too few local features around the vertebra. Finding a remedy to this problem is one of the aims of this project.

Work package 3: System demonstrators

Demonstrator 1: RANSAC for simplified models. RANSAC is one of the most frequently used algorithms in computer vision and there exists a huge amount of variants. However, most of them aim for increased speed or increased accuracy under common statistical assumptions. In contrast, we will develop a similarly efficient technique for model fitting, but robust to the type of model errors that arise from using simplified models of the image generation process. We will demonstrate its effectiveness on a number of classical computer vision problems.
Demonstrator 2: Multi-atlas segmentation of 3D images. The first demonstrator is a system for multi-atlas segmentation based on feature detectors and descriptors that have been specialized for use on 3D medical images. The aim is to illustrate the speed and robustness that can be achieved with feature-based registration when properly adapted for the medical image domain. Feature-based registration techniques specialized for the multi-atlas setting can increase the computational efficiency by orders of magnitude and thereby enabling the use of significantly larger number of atlas images.

This system demonstrator builds on several of the developed components in the two other work packages. First, we will use the framework of feature modelling and matching (Task 2.1) for establishing hypothetical correspondence matches between the different images. Then, we will apply the robust and efficient image registration techniques of Task 1.1. These are the basic tools needed in order to construct the feature-based atlas models of Task 2.2.

We will evaluate the demonstrator on standard benchmarks including brain atlases [19] and cardiac segmentation [16], see Fig. 2, but also on more challenging set-ups such as multi-organ segmentation of CT and MR images where subjects tend to have high shape and positional variability. We will also test the demonstrator in close collaboration with our medical partners on many clinically relevant problems such as quantification of pericardial fat, detection of bone metastases in PET/CT, detection and classification of plaque in carotid arteries.

4 Significance

In computer vision, feature-based estimation methods have become a standard reliable tool for solving certain types of 2D imaging problems. The goal of this research is that feature-based estimation should be an equally reliable tool in 3D image analysis. This would not only make it easier for researchers but also for non-imaging experts, for instance, medical staff by making available robust registration methods that do not require a user with technical expertise. In our preliminary work, we have seen that feature-based registration outperforms the intensity-based methods in terms of ro-

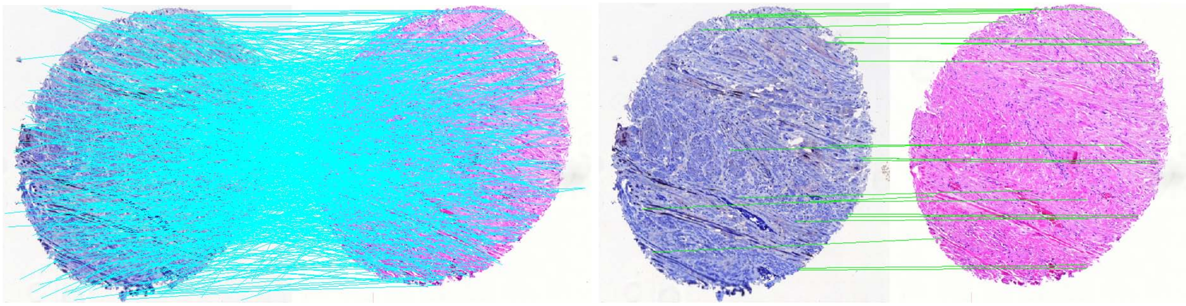

Figure 3: (Left) Images of two different stainings from a prostate biopsy with 791 hypothetical correspondences (cyan) obtained from SIFT. (Right) Same images, but now with 21 inlier correspondences (green) of the optimal truncated L_2-fit over all rigid transformations. The running time of our MATLAB implementation is 3s.

bustness and ease of use while being ten or even a hundred times faster. If these improvements can be commonly available for a whole class of problems, then this will represent a major step forward.

Furthermore, the lessons learned from this project will be applied in practice in several other research projects, particularly, in collaboration with our medical partners on clinically relevant problems such as quantification of pericardial fat and detection of bone metastases in PET/CT. An example is the Swedish CArdioPulmonary bioImage Study (SCAPIS), which is one of the biggest research projects ever to be carried out in Sweden in the field of heart, blood vessel and lung diseases. It will be the world's largest and most comprehensive imaging based population study aiming at a total recruitment of 30.000 subjects. The applicant is closely connected to this consortium and is collaborating with Prof. Göran Bergström, the PI for SCAPIS, who made the following statement about the importance of developing automated imaging methods:
"SCAPIS will generate large sets of imaging data of both CT and MR and manual analysis is not possible. To capitalize on this enormous data bank we are in great need of automated methods. Worldwide this is an area of intense research, and it is essential for Swedish society and industry to have cutting-edge knowledge in this important field. Methods based on optimization and machine learning are key technologies in this regard."

Collaboration. In this proposal, MedTech West and its network of medical researchers and industry will be essential. Likewise, Prof. Göran Bergström's group at Gothenburg University, Prof. Lars Edenbrandt at Gothenburg University and Skåne University Hospital and Prof. Jonas Erjefält at Lund University will be other important collaborators.

5 Preliminary results

Recently, we have worked on robust and reliable registration methods for low-dimensional transformation models, such as rigid and affine transformations. Despite highly non-convex loss functions, such as the truncated L_2-loss, we have been able to design efficient optimization algorithms that are guaranteed to find the optimal solution (hence independent of initialization). See Fig. 3 for one example from [2] of 2D medical image registration. These results have inspired us to more difficult problems such as registering two whole-body CT images. Clearly, there is no low-dimensional registration model that will perfectly align two such images. Still, using standard 3D feature descriptors (but without scale invariance) [4] to obtain point correspondences across different subjects in combination with efficient optimization techniques, it is possible to advance state of the art in medical

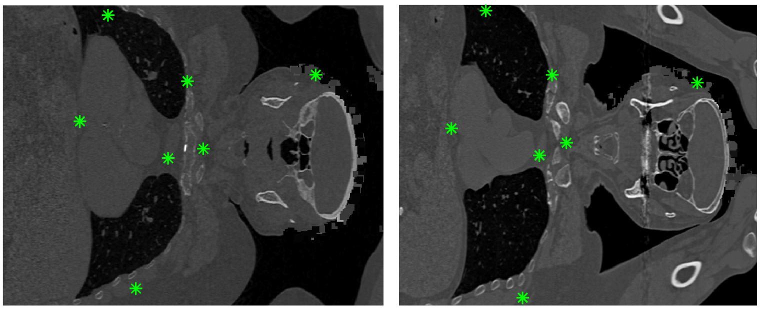

Figure 4: (Left) Close-up of a whole-body CT image (one slice) with the detected feature points. (Right) Corresponding feature points automatically matched in a CT scan of another subject under an affine transformation.

image registration, in terms of robustness to initialization and computational efficiency [9]. See Fig. 4 for an example showing a close-up of detected and matched features from one slice in a pair of CT images. Examining the error residuals, it is clear that the model errors are not independent Gaussian noise, which motivates the investigation of modelling model error in the first work package. It also demonstrates that our approach for feature-based multi-atlas segmentation in the second work package is technically sound and feasible.

Another line of research that we have pursued is concerned with large-scale 3D reconstruction of scene geometry and camera motion from collections of ordinary, unsorted 2D images. Here, the modelling of outlier correspondences and robust estimation techniques are the main challenges. Our work, which received the Best Paper Award at the OMNIVIS conference in 2011 [7], is the basis for a fully automated system for 3D reconstruction. Using depth sensors, the same type of 3D reconstruction system is possible, but the error characteristics of such sensors is much more uncertain and sometimes seemingly random. So far, there is no widely accepted mathematical model that accounts for the modelling errors.

Independent line of research. Although I have chosen to work closely with former supervisor, Prof. Fredrik Kahl, I have been independent in chosing research topics and directions. For much of our common work on model estimation in the presence of outliers, I have taken the initiative and come up with the central ideas. Moreover, this proposed research project represents a new line of research for me and independent of colleagues and collaborators — with less focus on optimization and more inclined towards mathematical modelling. Even though I will continue to work with Prof. Fredrik Kahl, I would pursue this project independently and I think it would broaden the scope of our department.

Another indication of my independence is that I am co-supervising several different PhD students with different main supervisors: Fangyuan Jiang (main supervisor: Fredrik Kahl), Erik Ask (main supervisor: Kalle Åström) and Linus Svärm (main supervisor: Magnus Oskarsson). I look forward to supervising my own PhD students in the near future. Note that several of my Master students that I have supervised on my own have continued to do a PhD.

Employment status. I hold a position as Assistant Professor at Chalmers University of Technology at least until 2017-07-31. If I pass an evaluation at that point in time, then my position will be made permanent. To pass the evaluation it is important to have obtained the Docent title and to have individual funding. I expect to obtain a Docent during this year. Hence, if I am granted funding from Vetenskapsrådet, I have very good chances to secure a permanent position at Chalmers.

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[15] M. Reuter, H. Rosas, and B. Fischl. Highly accurate inverse consistent registration: a robust approach. *Neuroimage*, 57(1):19–21, 2010.

[16] R. Shahzad, D. Bos, C. Metz, A. Rossi, H. Kirisli, A. van der Lugt, S. Klein, J. Witteman, P. de Feyter, W. Niessen, L. J. van Vliet, and T. van Walsum. Automatic quantification of epicardial fat volume on non-enhanced cardiac CT scans using a multi-atlas segmentation approach. *Medical Physics*, 40(9):1–9, 2013.

[17] A. Sotiras, C. Davatzikos, and N.Paragios. Deformable medical image registration: A survey. *IEEE Trans. Medical Imaging*, 32(7):1153–1190, 2013.

[18] J. Sturm, N. Engelhard, F. Endres, W. Burgard, and D. Cremers. A benchmark for the evaluation of RGB-D SLAM systems. In *IROS*, 2012.

[19] H. Wang, J. Suh, S. Das, J. Pluta, C. Craige, and P. Yushkevich. Multi-atlas segmentation with joint label fusion. *IEEE Trans. Pattern Analysis and Machine Intelligence*, 35(3):611–623, 2013.

[20] Q.-Y. Zhou and V. Koltun. Simultaneous localization and calibration. In *Conf. Computer Vision and Pattern Recognition*, 2014.

Interdisciplinarity

My application is interdisciplinary

☐

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

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

Budget and research resources

Project staff

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

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

Dedicated time for this project*

	Role in the project	Name	Percent of full time
1	Applicant	Olof Enqvist	50
2	Participating researcher	Doktorand	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	2019	Total
1	Applicant	Olof Enqvist	50	398,000	412,000	426,000	441,000	1,677,000
2	Participating researcher	Doktorand	80	435,000	450,000	466,000	482,000	1,833,000
	Total			833,000	862,000	892,000	923,000	3,510,000

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	60,000	62,000	64,000	66,000	252,000
	Total	60,000	62,000	64,000	66,000	252,000

Running Costs

	Running Cost	Description	2016	2017	2018	2019	Total
1	Driftskostnader	Obligatoriska	18,000	19,000	20,000	20,000	77,000
	Total		18,000	19,000	20,000	20,000	77,000

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	833,000	862,000	892,000	923,000	3,510,000		3,510,000
Running costs	18,000	19,000	20,000	20,000	77,000		77,000
Depreciation costs					0		0
Premises	60,000	62,000	64,000	66,000	252,000		252,000
Subtotal	911,000	943,000	976,000	1,009,000	3,839,000	0	3,839,000
Indirect costs	306,000	316,000	327,000	339,000	1,288,000		1,288,000
Total project cost	1,217,000	1,259,000	1,303,000	1,348,000	5,127,000	0	5,127,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

All costs except the salaries for me and one PhD student are compulsory overhead costs at Chalmers.

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 for Olof Enqvist, 810106-1995

1. Academic degree

2006 Master of Science and Technology, Linköping University, Master's thesis performed at ZF Lenksysteme in Schwäbisch Gmünd, Germany.

2. Degree of Doctor

2011 PhD in Applied Mathematics, Lund University. Thesis: 'Robust Algorithms for Multiple View Geometry. Opponent: Prof. Marc Pollefeys, ETH Zürich. Advisors: Prof. Fredrik Kahl and Prof. Kalle Åström.

3. Postdoctoral positions

2011–2013 Postdoctoral researcher, Centre for Mathematical Sciences, Lund University.

6. Present appointment

2013– Assistant Professor, Department of Signals and Systems, Chalmers University of Technology. 100% research. Four-year appointment.

7. Previous appointments

2011–2013 Co-founder of Arkivbyrån AB, selling a website archiving service.

2004–2005 Teaching assistant, Department of Automatic Control, Linköping University.

2003–2003 Teaching assistant, Department of Mathematics, Linköping University.

8. Supervision

PhD Students As co-supervisor for Erik Ask (PhD 2014), Linus Svärm(PhD 2015), Fangyuan Jiang (2011-), Frida Fejne (2015-).

Master Theses Hanna Källén (2009, now PhD Student), Linus Svärm (2009, now PhD Student), Tobias Palmér (2010, now PhD Student), Andreas Pössl (2012), Nils Bore (2012, now PhD Student), Mikael Holmquist (2012), Alexander Norlén (2014), Jennifer Alvén (2014, now PhD student), Juan Pedro Vigueras Guillén (2015, now PhD student), .

10. Further particulars

2013 Best Nordic Thesis Honourable Mention a bi-annual award to the best thesis in the fields of pattern recognition and image analysis.

2012 Outstanding reviewer Conf. on Computer Vision and Pattern Recognition (CVPR).

2011 Best Paper Award at the 11th workshop of OMNIVIS, Barcelona, Spain, (1st author).

2006 Tryggve-Holm Medal, 2005-2006, for having the best grade at the master program.

Reviewing Conferences: ICCV, ECCV, CVPR, ICPR, SCIA. Journals: PAMI, IJCV.

Publication list

Olof Enqvist, 810106-1995

Publication List of Olof Enqvist, 2008-2015

Note: the major international conferences in the field of computer vision are *ICCV*, *ECCV*, *CVPR*, all which have a below 25% acceptance rate. The major journals (in terms of impact factors) are *International Journal of Computer Vision* and *IEEE Transactions on Pattern Analysis and Machine Intelligence*. Google Scholar was used to count citations. Auto-citations were not removed.

1. Refereed Journal Publications[1]

* [1] Enqvist, O., Ask, E., Kahl, F., Åström, K., Tractable Algorithms for Robust Model Estimation, *International Journal of Computer Vision*, 2014. Conference versions at ECCV 2012 and CVPR 2013. Citations: 12.

[2] Jiang, F., Enqvist, O., Kahl, F., A Combinatorial Approach to L_1 Matrix Factorization, *Journal of Mathematical Imaging and Vision*, 2014.

[3] Palmér, T., Tamtè, M.; Halje, P.; Enqvist, O.; Petersson, P., A system for automated tracking of motor components in neurophysiological research, *Journal of Neuroscience Methods*, 2012. Citations: 3.

[4] Enqvist, O., Kahl, F., Olsson, C., Åström, K., Global Optimization for One-Dimensional Structure and Motion Problems, *SIAM Journal of Imaging Science*, 2010. Conference version at ICCV 2007. Citations: 14.

2. Refereed Conference Publications (whose results are not available elsewhere)

[5] Alvén, J., Norlén, A., Enqvist, O., Kahl, F., Überatlas: Robust Speed-Up of Feature-Based Registration and Multi-Atlas Segmentation, Scandinavian Conference on Image Analysis, Denmark, 2015.

* [6] Svärm, L., Enqvist, O., Kahl, F., Oskarsson, M., Improving Robustness for Inter-Subject Medical Image Registration Using a Feature-Based Approach, *Proc. International Symposium on Biomedical Imaging*, USA, 2015.

* [7] Ask, E., Enqvist, O., Svärm, L., Kahl, F., Lippolis, G., Tractable and Reliable Registration of 2D Point Sets, *Proc. European Conference on Computer Vision*, Switzerland, 2014.

[1] More journal publications are in the pipeline.

* [8] Svärm, L., Enqvist, O., Kahl, F., Oskarsson, M., Accurate Pose Estimation and Localization for Large-Scale 3D Models, *Proc. Conference on Computer Vision and Pattern Recognition*, USA, 2014. Citations: 1.

[9] Fredriksson, J., Enqvist, O., Kahl, F., Fast and Reliable Two-View Translation Estimation, *Proc. Conference on Computer Vision and Pattern Recognition*, USA, 2014.

[10] Jiang, F., Enqvist, O., Kahl, F., Åström, K., Improved Object Detection and Pose Using Part-Based Models, *Proc. Scandinavian Conference on Image Analysis*, Finland, 2013.

[11] Svärm, L., Simayijiang, Z., Enqvist, O., Olsson, C.., Point Track Creation in Unordered Image Collections Using Gomory-Hu Trees, *Proc. International Conference on Pattern Recognition (ICPR)*, Japan, 2011. Citations: 1.

*[2] [12] Enqvist, O., Olsson, C., Kahl, F., Non-Sequential Structure from Motion, *Proc. 11th Workshop on Omnidirectional Vision, Camera Networks and Non-Classical Cameras (OMNIVIS)*, Barcelona, Spain, 2011. Citations: 20.

[13] Enqvist, O., Jiang, F., Kahl, F., A Brute-Force Algorithm for Reconstructing a Scene from Two Projections, *Proc. Conference on Computer Vision and Pattern Recognition (CVPR)*, Colorado Springs, USA, 2011. Citations: 6.

[14] Olsson, C., Enqvist, O., Stable Structure from Motion for Unordered Image Collections, *Proc. Scandinavian Conference on Image Analysis (SCIA)*, Ystad, Sweden, 2011. Citations: 14.

[15] Källén, H., Ardö, H., Enqvist, O., Tracking and Reconstruction of Vehicles for Accurate Position Estimation, *Worksh. Applications in Computer Vision (WACV)*, Hawai, USA, 2011. Citations: 1.

[16] Enqvist, O., Kahl, F., Two View Geometry Estimation with Outliers, *Proc. British Machine Vision Conference (BMVC)*, London, UK, 2009. Citations: 9.

[17] Enqvist, O., Josephson, K., Kahl, F., Optimal Correspondences from Pairwise Constraints, *Proc. International Conference on Computer Vision (ICCV)*, Kyoto, Japan, 2009. Citations: 47.

[18] Enqvist, O., Kahl, F., Robust Optimal Pose Estimation, *Proc. European Conference on Computer Vision (ECCV)*, Marseille, France, 2008. Citations: 26.

[2] Best Paper Award at OMNIVIS 2011.

[19] Olsson, C., Enqvist, O., Kahl, F., A Polynomial-Time Bound for Matching and Registration with Outliers, *Proc. Conference on Computer Vision and Pattern Recognition (CVPR)*, Anchorage, USA, 2008. Citations: 27.

3. Books, Book Chapters and Surveys

[20] Enqvist, O., Robust Algorithms for Multiple View Geometry, *PhD Thesis*, Centre for Mathematical Sciences, Mathematics, Lund University, 2011.

[21] Enqvist, O., Correspondence Problems in Geometric Vision, *Licentiate Thesis*, Centre for Mathematical Sciences, Mathematics, Lund University, 2009.

CV

Name: Olof Enqvist	**Doctorial degree:** 2011-05-30
Birthdate: 19810106	**Academic title:** Doktor
Gender: Male	**Employer:** No current employer

Research education

Dissertation title (swe)

Robust Algorithms for Multiple View Geometry: Outliers and Optimality

Dissertation title (en)

Robust Algorithms for Multiple View Geometry: Outliers and Optimality

Organisation	Unit	Supervisor
Lunds universitet, Sweden Sweden - Higher education Institutes	Matematikcentrum 107150	Fredrik Kahl

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
10199. Annan matematik	ISBN 978-91-7473-102-6	2011-05-30

Publications

Name: Olof Enqvist	**Doctorial degree:** 2011-05-30
Birthdate: 19810106	**Academic title:** Doktor
Gender: Male	**Employer:** No current employer

Enqvist, Olof 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.