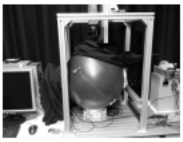
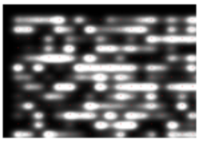
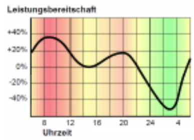
HOCHSCHULE KONSTANZ
TECHNIK, WIRTSCHAFT UND GESTALTUNG

institut für optische systeme | konstanz

optische messtechnik | bildverarbeitung | lichttechnik







institute for optical systems

annual report 2014

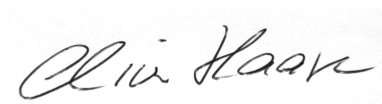
Foreword

Hochschule Konstanz University of Applied Sciences (HTWG) has been one of the first Universities of Applied Sciences that has clearly committed itself to applied research. Today, HTWG has positioned itself in the growing group of research active Universities of Applied Sciences, and is continuously striving for even greater excellence, visibility, and leadership.

The research institutes play an essential role in the overall research activities of HTWG. The Institute for Optical Systems (IOS) has been founded as one of three focus institutes in 2008, and has lived up to its mission and HTWG's expectation ever since.

Measuring the success of research is generally a difficult task. It becomes easy, however, for individuals and institutes alike that contribute to the scientific community in many different ways. The IOS clearly is such an institute. Its members have published their work in numerous high quality publications, they have acquired substantial amounts of external funding, and they have successfully led several doctoral candidates to their advanced degree, to name only the most obvious contributions. The institute's success has only been possible because of the enthusiasm of its members, and its tight integration with HTWG. Students have contributed to the research work on various levels, and the results have been fed into the members' teaching. In this sense, the IOS has demonstrated the importance of excellent applied research also as a means for high quality teaching, in particular on the graduate level.

I am proud to write these few lines of thanks and congratulations for the IOS and cordially wish the institute, but first and foremost its members, ongoing enthusiasm, thirst for knowledge, and success for the future.



Prof. Dr. Oliver Haase
Vice-President for Research, University of Applied Sciences Konstanz

Preface

The present report gives an overview over the research and development activities of the Institute for Optical Systems (IOS) Konstanz in the year 2014. Our main fields of interest are cognitive systems, geometric modelling, image processing, optical metrology and light engineering, thus representing the fundamental disciplines of current optical technology. The focus on optical systems as a whole allows us to offer competent partnership to the local industry in all relevant aspects. The IOS was founded in April 2008 by four professors from three different faculties of the University of Applied Sciences at Konstanz and is led by Prof. Dr. Umlauf (director) and Prof. Dr. Franz (associate director).

The following project descriptions present ongoing activities mainly on a status report level. Most of the reports are written by students working on their diploma, bachelor, master or Ph.D. theses. They reflect the largely varying levels of content, practice and insight that are characteristic for an institution involved in academic education. Due to its interdisciplinary nature, research at the IOS combines approaches from optics, computer graphics, image and signal processing, metrology, light engineering and sensor technology typically resulting in optical systems on a prototype level, either in pre-phase research or in cooperation with local industry.

On the occasion of our annual report, we would like to thank all of our students and co-workers for their enthusiasm and dedication which makes our institute a great place to be. Special thanks go to our institute officers, Pascal Laube and Michael Grunwald, and to Jürgen Keppler for smoothly managing our day-to-day activities. We are also indebted to the administration and staff of the HTWG Konstanz for their help, especially president Dr. Carsten Manz and Prof. Dr. Oliver Haase, for their support and for continuing the start-up funding, and the faculties of Mechanical Engineering, Electrical and Information Engineering, and Computer Science with the deans Prof. Dr. Thomas Böttcher, Prof. Dr. Thomas Birkhölzer and Prof. Dr. Jürgen Neuschwander for their assistance. Furthermore we appreciate the support of the Institute for Applied Research (IAF) Konstanz, especially Prof. Dr. Horst Werkle and Dipl.-Ing. FH Andreas Burger.

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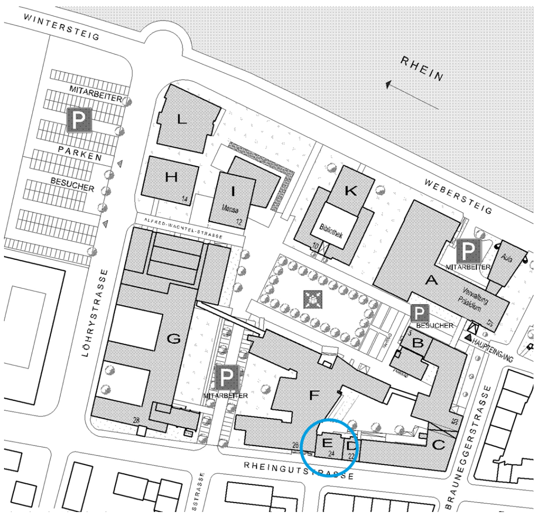
Institute Profile

IOS Building and Location Plan

Institute for Optical Systems

Brauneggerstraße 55
Building E
3rd and 4th floor
78462 Konstanz



Location Plan

Institute Members

Prof. Dr. Georg Umlauf:

Diploma in computer science from University of Karlsruhe, 1996. Doctoral degree in computer science from University of Karlsruhe, 1999. PostDoc at University of Karlsruhe and University of Florida, Gainesville, USA, 1999-2000. Software development and senior researcher at Tebis AG, Hamburg, 2000-2002. Assistant professor for geometric algorithms at University of Kaiserslautern, 2002-2009. Interim professor for computer graphics at University of Karlsruhe, 2009. Since 2009 professor for computer graphics at University of Applied Sciences Konstanz and head of the computer graphics lab. Since 2010 member of the 'Institute for Optical Systems (IOS)' and 'Institute for Applied Research (IAF)'. Main research interests: Computer graphics, geometric modeling (splines, subdivision), reverse engineering, physical simulations.

Prof. Dr. Matthias Franz:

M.Sc. in Atmospheric Sciences from SUNY at Stony Brook, Diploma in physics from the Eberhard-Karls-Universität, Tübingen and doctoral degree in 1998. Thesis research in visual insect and robot navigation at the MPI for Biological Cybernetics and as a PostDoc at the Australian National University in Canberra. In industry he worked on various aspects of autonomous vision systems. 2002, he returned to the MPI as a group leader in the area of machine learning and computer vision. Since 2007 professor at the University of Applied Sciences in Konstanz and head of cognitive systems lab. Member of 'Institut für Angewandte Forschung (IAF)'. Main research activities in the development of automatically generated vision systems, optimisation and probabilistic modeling, with applications in industrial machine vision, texture analysis and steganalysis.

Prof. Dr. Claus Braxmaier:

Diploma in precision engineering at University of Applied Sciences Furtwangen. Diploma in physics and doctoral degree at the University of Konstanz in the field of fundamental tests of physics. Post-Doc at University of Konstanz. At EADS Astrium GmbH, system responsible for scientific and earth observation missions for ESA and head of group 'Mission Metrology'. Since 2005 professor for physics and control theory at the University of Applied Sciences Konstanz. Member of 'Institut für Angewandte Forschung' and 'Institut für Naturwissenschaften und Mathematik' Konstanz. Since 2014 ZARM Deputy Executive Director, Director Space Technology. Main research: high resolutionoptical metrology for industrial and space applications.

Prof. Dr. Bernd Jödicke:

Study of physics at the University of Kalrsruhe. Doctoral degree at Technical University Hamburg and University Karlsruhe in the field of high frequency technology. After that, industrial work at ABB Baden, Switzerland, as executive director for R&D. Since 1992 professor for applied physics at University of Applied Sciences Konstanz. Member of 'Institute for Applied Research (IAF)', 'Institut für Naturwissenschaften und Mathematik (INM)', 'Institute for Optical Systems (IOS) Konstanz' and 'Deutsche Lichttechnische Gesellschaft'. Head of laboratory for light engineering at HTWG. Main research activities in color and light measurements and color camera systems.

Prof. Dr. Burkhard Lehner:

Diploma in computer science from University of Kaiserslautern, 2004. Doctoral degree in computer science from University of Kaiserslautern, 2008. Software development at Sirona Dental System GmbH, Bensheim, 2008-2013. Since 2013 professor for computer science at University of Applied Sciences Konstanz. Since 2014 member of the 'Institute for Optical Systems (IOS)'. Main interests: software development, computational geometry, optical 3D measurement (especially in dental CAD/CAM).

Prof. Dr. Klaus-Dieter Durst:

Study of physics at the University of Stuttgart, 1986 doctoral degree in the field of magnetism at the Max-Planck-Institute of metal research. Thereafter research center Weissach of the Dr. Ing. h.c. F. Porsche AG, responsible for the central unit 'measurement technologies'. Since 1993 professor for measurement engineering and sensor technology at the University of Applied Sciences Konstanz. Member of 'Institut für Naturwissenschaften und Mathematik' and 'Institute for Optical Systems' Konstanz. Head of laboratories for measurement and sensor technology and production metrology. Currently director of 'Institut für Naturwissenschaften und Mathematik' Konstanz. Activities in the accreditation and surveillance of testing laboratories and inspection bodies.

IOS Staff

Professors	Georg Umlauf, director IOS Matthias Franz, associate director IOS Claus Braxmaier Bernd Jödicke Burkhard Lehner Klaus-Dieter Durst
Officer	Pascal Laube
Academic Staff	Leonard Thießen Markus Oswald Markus Meßmer Michael Grunwald Johannes Stühler Marco Fehrenbach Jens Müller Manuel Caputo Daniel Scherz
Postdoc	Thilo Schuldt
PhD Students	Martin Schall Pascal Laube Klaus Denker Jürgen Keppler Roman Byshko Dang Le Ruven Spannagel
Student Assistants	Martin Miller Korkiat Khumphai

External Fundings and Grants

- Baumer Inspection GmbH, Konstanz: "Farbtexturen in der industriellen Oberflächeninspektion", contract research.
- Baumer Inspection GmbH, Konstanz: "Inline - Inspektionstechnologie zum Farbabgleich für den digitalen Dekordruck", contract research.
- Australian Research Council, Pattern recognition in animals and machines: using machine learning to reveal cues central to the identification of individuals, Discovery Projects Grant.

Cooperations with Research Institutions and Industry

Academic and Institutional Cooperations

- University of Queensland, Brisbane
- Humboldt-Universität zu Berlin
- ZARM (drop tower), Center of Applied Space Technology and Microgravity, Bremen
- DLR Institut für Raumfahrtsysteme Bremen
- University of Tübingen
- Max-Planck-Institute for Biological Cybernetics, Tübingen
- German Federal Office for Information Security (BSI), Bonn
- Universität Konstanz
- University of California, Davis
- Technische Universität Kaiserslautern
- University of Florida, Gainesville
- Grenoble Institute of Technology
- University of Strasbourg

Industry Cooperations

- Siemens Postal, Parcel & Airport Logistics GmbH, Konstanz
- Sirona GmbH, Bensheim
- EADS Astrium, Immenstaad
- Breuckmann GmbH, Meersburg
- Chromasens GmbH, Konstanz
- Baumer Inspection GmbH, Konstanz
- Procon-System GmbH, Thierstein
- Lightdesign-Solutions GmbH, Dresden

- Knotenpunkt, Wenzel Präzision GmbH, Balingen
- Tebis AG
- Liebherr Aerospace GmbH, Lindenberg
- NTT Data Deutschland GmbH
- Lacuna Solutions GmbH

Theses and Student Projects

PhD Theses

- Pham Hai Dang Le, Detection of Steganography in Images with Statistical Models, Konstanz, 2014.

Master Theses

- Markus Friedrich , A parallel hash map for LOD-aware depth-map fusion, 2014.
- Michael Grunwald , Farbseparation im Tiefdruck, 2014.
- Martin Schall, Kamerakalibrierung mit Gaußschen Prozessen, 2014.
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- Andreas Bug, Superresolution image reconstruction for barcode and optical character recognition applications, 2014.
- Rüdiger Schneider, Motivsuche in Proteinsequenzen, 2014.

Bachelor Theses

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- Jonas Bublin, Vergleich und Bewertung von 3D-Rekonstruktion mit Commodity-Hardware, 2014.
- Leonard Thießen, Merging Multiple 3D Face Reconstructions, 2014.
- Patrick Roßnagel, Hand-held scanning of geometric primitives in virtual reality, 2014.

Student Projects

- Marco Fehrenbach, Korkiat Khumphai, Felix Schuckert, On-line splat rendering, 2014.
- Mirko Indlekofer, Fabio Blaschke, VCam, 2014.

Publications

Journal Papers

- Aguilera, D. N., H. Ahlers, B. Battelier, A. Bawamia, A. Bertoldi, R. Bondarescu, K. Bongs, P. Bouyer, C. Braxmaier, M.O.Franz, et al., "STE-QUEST ? Test of the universality of free fall using cold atom interferometry", Classical and Quantum Gravity, vol. 31, no. 11, pp. 115010, 2014.

Conference Proceedings

- Thießen, L., P. Laube, M. O. Franz, and G. Umlauf, "Merging multiple 3d face reconstructions", Symposium on Information and Communication Systems, pp. 7-12, 2014.

- Caputo, M., K. Denker, M. O. Franz, P. Laube, and G. Umlauf, "Learning geometric primitives in point clouds", Symposium on Geometry Processing, Cardiff 2014, 2014.

Poster Presentations

- Caputo, M., K. Denker, M. O. Franz, P. Laube, and G. Umlauf, "Learning geometric primitives in point clouds", Symposium on Geometry Processing, Cardiff 2014, 2014.

3d Laboratory

The IOS 3d Laboratory is split it two parts which are located in buildings F and E of HTWG and are led by Prof. Georg Umlauf. The 3d laboratory infrastructure mainly consists of devices for 3d capture and visualization.
A 3d projection system based on circularly polarized Sanyo XWGA projectors is able to create a 3d display for large audiences. The projectors have a resolution of 1280x800 and a brigthness of up to 5.000 Lumens.
The Faro Edge 3d ScanArm is a handheld laser scanner that is able to capture 3d data of real life objects. The Scanner is able to capture data points with an accuracy of $\pm 25\mu m$. Further capture devices include multiple microsoft kinects as well as a multi-camera stereo-matching system that can be used for realtime face reconstruction. All of the 3d Laboratory's workstations are equipped with high performance graphics cards.

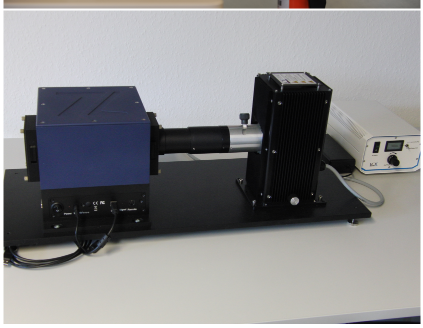
Image Sensor Laboratory

The Image Sensor Laboratory is located in building E of HTWG and is led by Prof. Matthias O. Franz. It is used to build, evaluate and calibrate the various camera systems used in the image processing projects of the IOS.

Preliminary experiments are run directly in the IOS main office in a laboratory section which can be isolated with a light-proof curtain, whereas higher precision experiments are done in various laboratories on the HTWG campus with appropriate facilities. For high-resolution multispectral imaging, we dispose of a Peltier-cooled pco.4000 14 bit camera with a 4008 $\times$ 2672 CCD array and a VariSpec Tunable Filter that allows for selecting an arbitrary 30 nm wide band in the visual range via a computer interface.

For inspecting and processing colour images, we use a specialised graphics workstation with a high-fidelity calibrated colour display. Spectral measurements are done with a KonicaMinolta CS 2000 absolute spectrometer.

In applications requiring high CCD sensor sensitivities (such as the optical radar project), we have another Peltier-cooled pco.1600 colour camera with a 1200 $\times$ 1600 CCD array, but higher sensitivity.



Computing Infrastructure

The compute and network environment of the institute is based on Intel and AMD multicore architectures connected with 1 GBit Ethernet. The 20 workstations use the operating systems Ubuntu Linux, Microsoft Windows and Mac OS. The central file server is integrated in the cluster system. For computation-intensive applications, such as multi-spectral image processing or the training of learning machines, we run a compute cluster under Ubuntu Linux. The cluster consists of a master node and a compute node with Intel Xeon CPUs, providing 40 processor kernels and 256 GB of RAM. Both nodes are mounted in a liquid-cooled rack with a 10 kW UPS. The internal cluster communication uses 2 GBit Ethernet and connects via FibreChannel to a RAID 6 storage system with 3.5 TB capacity to guarantee a high data throughput. Resources are managed with the SUN GridEngine. The cluster is connected to the backbone of the HTWG network via 10 GBit FibreChannel. Data backup is guaranteed by the central computer services of the HTWG.

Research Activities

A parallel hash map for LOD-aware depth-map fusion

Markus Friedrich, Bernd Hamann[1], Oliver Deussen[2], Georg Umlauf

We introduce a real-time and memory-efficient solution to the problem of depth-map fusion and level-of-detail aware (LOD-aware) spatial data storage. Image-space 3-d reconstruction methods result in a set of view-dependent depth-maps. In most cases, an additional depth-map fusion mechanism in combination with a spatial data storage scheme is employed to assemble and store complete 3-d models. Our approach guarantees memory efficiency by using a sophisticated hash mapping approach that can distinguish different data LODs depending on the data resolution of the input depth-maps. It is inherently better suited for modern graphics processing units (GPUs) than tree-based data structures and allows for efficient iterative data updates. The described depth-map fusion method is optimized for massive parallel processing which enables real-time performance. An evaluation of our depth-map fusion and spatial data storage solution demonstrates its applicability in the field of real-time 3-d reconstruction.

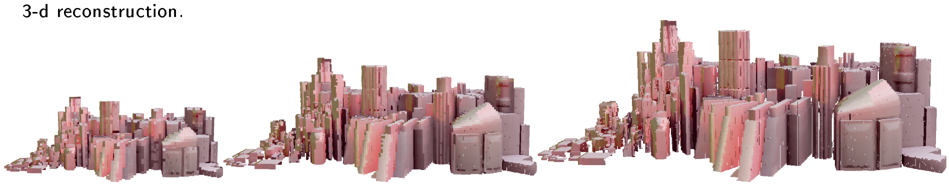


Figure 1: Renderings of a city voxel model stored at different level of details. The discussed data structure scheme exploits depth-map resolution and object-sensor distance for level-of-detail-aware, memory-efficient spatial data storage. This can be achieved without loss of geometric detail.

Introduction

In the context of image-space 3-d reconstruction, most systems implement a process pipeline consisting of three steps. In the first step a depth-map is computed and de-noised based on calibrated camera images. In the second step, the fusion step, depth-map samples are integrated into a consistent and complete 3-d model. Some approaches apply additional refinement algorithms to the model that improve surface smoothness or model water-tightness [1, 2]. The third step stores the generated surface geometry in a specialized data structure optimized for spatial information.

For real-time reconstruction systems, computational efficiency is an additional requirement for the development of the fusion algorithm and its implementation. Its solution is always a trade-off between speed and result quality. The amount of computed surface data for dense reconstruction methods exceeds that of feature-based reconstruction methods by far. This implies strict requirements on the used spatial data structure. It should provide both, memory efficient data storage and run-time efficient data insertion and retrieval. Memory efficiency can be achieved by considering sparse data structures which, unlike grid-based solutions, do not occupy memory to represent empty space. LOD strategies, which store fusion data dependent on the depth-map resolution, can further streamline overall memory consumption. To achieve run-time efficiency, the massive parallel hardware architectures of modern GPUs can be used. They allow for real-time 3-d reconstruction without specialized and thus expensive hardware. Their potential can be exploited if all used algorithms and data structures minimize global thread synchronization and per-thread operation complexity. A survey of parallel programming models and tools was published in [3].

The fusion data structure should offer parallel voxel insertion and retrieval operations as well as a sparse and LOD aware storage scheme for memory efficiency. Due to the iterative nature of the fusion process, the used data structure should guarantee constant per-iteration insertion performance. The fusion process itself should be efficient enough for real-time depth-map fusion. It should provide efficient strategies for depth-map overlap detection

[1]University of California, Davis, USA
[2]University of Constance, Germany

and removal.

Current Status

Our reconstruction process consists of three steps, see Figure 2: In the first step a depth-map based on a stream of camera images is computed. Selected images are used to estimate corresponding camera poses. The plane-sweep method computes a depth-map which is de-noised for artifact removal. In the second step depth-maps are fused into a 3-d voxel model. In the third step generated voxels are inserted into a hash map-based data structure.

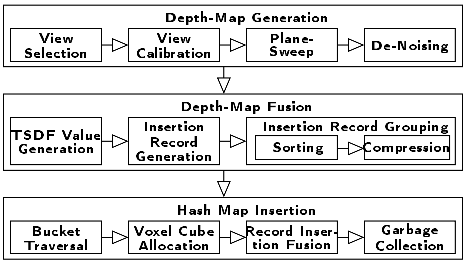


Figure 2: The three steps of the reconstruction pipeline.

This project introduces a parallel hash map data structure which is optimized for massively parallel hardware and sparse spatial voxel data. It is LOD-aware and addresses the problems of standard hierarchical approaches in terms of implementation complexity, meta-data overhead and flexibility. Unlike many other hash mapping techniques, it is well suited for iterative insertion scenarios.

The described depth-map fusion scheme parallelizes depth-map processing and addresses the problem of depth.map overlap using a simple and efficient merging strategy. To generate depth-maps we use calibrated video images as input. A single depth-map is computed based on three input images using the so-called plane-sweep method. It uses a corresponding point search with a color-based correlation measure in combination with a plane-based approach to exploit the epipolar geometry of the camera views for higher efficiency. The fusion scheme is applicable to real-time reconstruction and integrates with the underlying hash map structure.

In this project we made the following specific contributions:

- A parallel hash map data structure that supports different data LODs and is optimized for incremental insertion.
- A parallel fusion scheme that is optimized to exploit the performance of our hash map data structure.

Both contributions enable real-time depth-map fusion by exploiting the parallel processing capabilities of modern GPUs. For the fusion process we define real-time behavior

Results and Future Work

For the evaluation we used an Intel Core i7-870 quad-core processor with 8GB of available DDR3 system memory and a NVidia GeForce GTX 470 with 1280MB GDDR5 RAM. Figure 1 shows renderings of voxel models of the city model from [4] for different level of details leading to 240; 1920; 15360 allocated voxel cubes.

The evaluation results show the real-time suitability of the depth-map fusion and voxel retrieval process. The fusion process scales well with the number of allocated voxel cubes and hash map records. Thus, the hash map record insertion is the most time-consuming part of the fusion pipeline.

For future research we plan several possible extensions and improvements. The degree of parallelism decreases for an adverse ratio between number of insertion records and number of compressed insertion records. Splitting compressed insertion records that correspond to a large number of insertion records increases the degree of parallelism. In the current design, existing voxel data is completely erased when the LOD of its record is increased. A more elaborate approach could convert existing data to the new LOD preserving information.

Bibliography

[1] Zach C.: Fast and high quality fusion of depth maps. *ICCV* (2008).

[2] Zach C., Pock T., Bischof H.: A globally optimal algorithm for robust TV-L1 range image integration. *ICCV* (2007), 1–8.

[3] Diaz J., Munoz-Caro C., Nino A.: A survey of parallel programming models and tools in the multi and many-core era. *IEEE Trans. Parallel and Distributed Systems 23*, 8 (2012), 1369–1386.

[4] Crane K.: Keenan's 3d model repository. `http://www.cs.columbia.edu/~keenan/Projects/ModelRepository`, 2014. [Online; accessed 10/31/2014].

Support Vector Machines for Knot Placement in B-Spline Curve Approximation

Pascal Laube, Georg Umlauf, Matthias Franz

When approximating 2D data points by a B-spline curve one needs a suitable parametrization which includes the definition of the knot vector. With this work we present a method for creating a knot vector by means of machine learning. Our approach is based on three steps: feature extraction, classification and knot placement based on a suitability measure.

Introduction

A common problem in CAD reverse engineering is the selection of a suitable parametrization that produces computationally stable and optically satisfying results. Parametrization includes assigning a parametric value to each data point and the definition of a knot vector. While there exists a multitude of methods for parametrization of data points, algorithms for knot-vector construction are scarce. The ambition in knot placement is to minimize the approximation error with as few knots as possible. For each point cloud there exist an infinite number of possible knot vectors. Known methods are either based on heuristics or use uniform distribution of knots. We propose a method that is based on classification by a support vector machine and results in a suitability measure for knot locations in the parametric domain.

Methodology

To apply machine learning algorithms such as support vector machines a training phase is required. In the training phase the support vector machines are exposed to a large set of pre-classified points of a point cloud to learn to discriminate between the different classes. In case of knot placement these two classes decide whether the parametric value of a data point is a good candidate for a knot or not. Since there exists no one perfect knot vector, training data is created by exhaustively searching for a knot vector with positive approximation properties. We generate a 14-dimensional feature vector based on angular-, distance- and curvature-features of point relations. In this process local curvature maximum points are of special interest. The trained classifier is used to rate a parametric values suitability as a knot value. We adapt the averaging method by L. Piegl and W. Tiller [1] to take this suitability into account. This new Score Averaging method leads to an even distribution of knot values over the parametric domain that also considers a point clouds geometry.

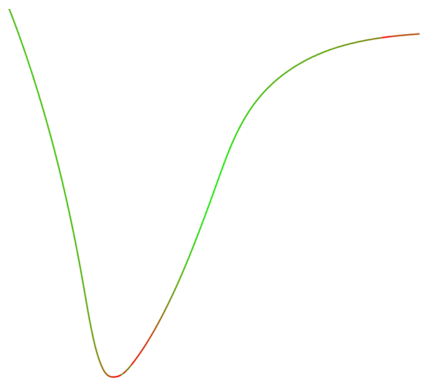


Figure 3: B-spline curve coloured according to knot suitability from red (highly suitable) to green (not suitable).

Current Status and Next Steps

Our method currently supports the creation of knot vectors for two-dimensional point data only. Obvious application for the trained machine learner would be the creation of knot vectors for surface approximation. Furthermore the approach has to be compared directly to other methods for performance evaluation.

Bibliography

[1] L. Piegl, W. Tiller: Surface approximation to scanned data, The visual computer 16.7, 2000, 386-395.

Merging Multiple 3D Face Reconstructions

Leonard Thießen, Pascal Laube, Georg Umlauf, Matthias Franz

We present a method to merge multiple 3D face reconstructions into one common reconstruction of higher quality. The individual three-dimensional face reconstructions are computed by a multi-camera stereo-matching system from different perspectives. Using 4-Points Congruent Sets and Iterative Closest Point the individual reconstructions are registered. Then, the registered reconstructions are merged based on point distance and reconstruction tenacity. To optimize the parameters in the merging step a kernel-based point cloud filter is used. Finally, this filter is applied to smooth the merged reconstruction. With this approach we are able to fill holes in the individual reconstruction and improve the overall visual quality.

Introduction

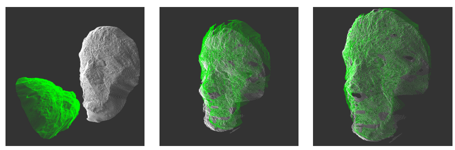
Face recognition is an important problem in biometric applications that is usually based on two-dimensional images. However, it has been shown that the recognition rate can be improved, if the recognition is based on 3D face reconstructions. This requires an accurate and fast reconstruction method, e.g. based on real-time multi-camera stereo-matching as presented in [1]. The algorithm is based on four synchronized cameras which captures images of a face from different perspectives . With this system it is possible to generate high-resolution depth images in real-time. This reconstruction also contains detailed information about the reconstruction tenacity. A bad matching pixel correspondence in the computation of the depth map will result in a low tenacity value for the reconstructed 3D point. As a result, the algorithm yields one 3D reconstruction of the captured face. The main focus of this approach was on recognition rate and reconstruction speed, reconstruction quality was not the main concern. Thus, the reconstructions may be noisy or have holes.

We propose a process to merge multiple reconstructions to improve the overall visual reconstruction quality. Due to the lack of a ground truth geometry the noise level is used as an additional quality measure during the merging process.

Merging 3D Face Reconstructions

The reconstruction system used captures a face from four different angles and uses multi-camera stereo-matching to compute a 3D reconstruction. The reconstructed geometry is represented as point cloud equipped with a measure to the quantify the local tenacity of the reconstruction. For details refer to [1]. Due to the speed of the reconstruction process several 3D reconstructions can be computed per second. These 3D reconstructions are usually from different perspectives since the person moves.

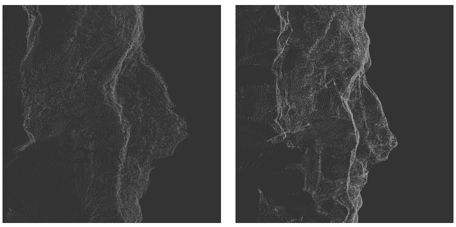
To merge these different 3D reconstructions we propose an approach consisting of four steps. First a coarse registration of the point clouds is done using 4-Points Congruent Set (4PCS) [2]. It's a global registration algorithm assuming no prior knowledge of the point clouds, so they can be in a arbitrary initial pose. This is followed by a fine registration using Iterative Closest Point (ICP). This algorithm tries to minimize the squared distances between neighbor points in both point clouds. An example of the entire registration process using 4PCS and ICP is shown in figure 4.



(a) (b) (c)

Figure 4: Registration of two example point clouds (a), after applying 4PCS (b), and after applying ICP (c).

The third step is to merge the registered point clouds to one 3D reconstruction using tenacity weighted interpolation. Each 3D reconstruction has regions where the point positions are more or less reliable. This is due to lighting effects, relative camera positions and orientations, etc. This reliability of a reconstructed point $\mathbf{p}$ is measured by the tenacity $t(\mathbf{p}) \in [0, 1]$, which is given as some weighted normalized cross-correlation of corresponding pixel neighborhoods in the four camera images, see [1]. Smaller values for t indicate higher point tenacity. Having several 3D reconstructions of the same face, a rather frontal reconstruction is usually reliable for forehead, nose, and mouth regions and unreliable for the cheeks. Thus, we chose a rather frontal reconstruction as reference reconstruction $\mathcal{P}_0$ that is enhanced and enriched be the additional reconstructions $\mathcal{P}_1, \ldots, \mathcal{P}_k$. The merged reconstruction $\mathcal{R} = \{\mathbf{r}_1, \ldots, \mathbf{r}_M\}$ is generated by adding points from one $\mathcal{P}_i, i = 0, \ldots, k$, or from a tenacity weighted interpolation of points from several $\mathcal{P}_i$ - depending on tenacity and point distances, there are five reconstruction parameters. In a last step the merged 3D reconstruction is filtered to erase noise. Due to the lack of a ground truth the result of the filter process can be used for quality measurement. If $\mathcal{R}_f = \{\mathbf{r}_1^f, \ldots, \mathbf{r}_M^f\}$ denotes the filtered reconstruction, the parameters are chosen such that $\mathcal{R}$ and $\mathcal{R}_f$ are close with respect to the error $e = \sum ||\mathbf{r}_i - \mathbf{r}_i^f||^2$, i.e. the filtering has minimal effect on $\mathcal{R}$, which denotes a high reconstruction quality. As point cloud filter we use the kernel-based filter method of Schall et al. [3]. Exemplary results of the filter process are shown in figure 5.



(a) (b)

Figure 5: Closeup of the nose of a joined reconstruction with optimized (a) parameters and after filtering (b).

Next Steps

The initial reconstructions that are merged later on contain color information which at the moment is lost in the interpolation step. For future work, point color has to be included in the process. Color information could be used when deciding point neighborhood as well as for lifelike visualization.

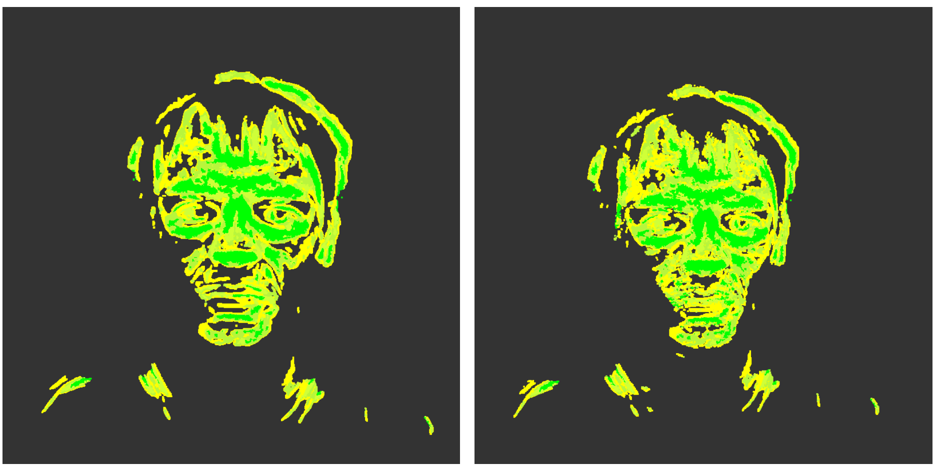
The presented method and the resulting parameters have shown to be optimal for reconstructions generated by the stereo-matching approach in [1]. To prove the general applicability of our algorithm data sets of other 3D face reconstruction systems need to be evaluated. The overall algorithm has not been optimized for real-time application yet.

Bibliography

[1] Klaus Denker and Georg Umlauf. An accurate real-time multi-camera matching on the gpu for 3d reconstruction. *Journal of WSCG*, 19:9–16, 2011.

[2] D. Aiger, N. J. Mitra, and D. Cohen-Or. 4-points congruent sets for robust surface registration. *ACM Transactions on Graphics*, 27(3):#85, 1–10, 2008.

[3] Oliver Schall, Alexander Belyaev, and Hans-Peter Seidel. Robust filtering of noisy scattered point data. In *Proceedings of the Second Eurographics / IEEE VGTC Conference on Point-Based Graphics*, pages 71–77, 2005.



(a) (b)

Figure 6: Tenacity colored images of a reference reconstruction (a) and the the respective merged reconstruction (b). The color gradient ranges from bright green (high tenacity) to yellow (bad tenacity).

On-line splat rendering

Marco Fehrenbach, Korkiat Khumphai, Felix Schuckert, and Georg Umlauf

Scanning real objects with the Faro Edge 3d ScanArm produces a large amount of geometrical points. Additionally during the scanning process the point cloud is able to grow dynamically or to replace a large area of points. The reconstruction of these points is very time consuming. To render a valid representation of the real object, we implemented a splat rendering process. The process uses the GPU to display the point cloud in real time. With this process the user is able to see the scanning results immediately.

Introduction

Scanning real objects is an important topic of computergraphics. An use case is to reconstruct the real object in a CAD representation. Another case is to identify the scanned object with the help of machine vision and learning. Nowadays the used hardware is very accurate and produces a large amount of useful data. For example the used Faro Edge 3d ScanArm. But the representation of the data is either very time consuming or needs additional interpretations. The solution is the implementation of a splat rendering process. The process directly uses the raw input data without any precomputations or additional requierements. Also it can handle the dynamic behaviour of the input data during the scan process. The result implementation is a part of an existing project to reconstruct CAD geometry [1].

Splat rendering process

The splat rendering process is based on the previous work of Botsch et. al. [2]. It uses the technique to expand the point size of the OpenGL pipeline. Then the normal of the point is used to discard single pixels of the point sprite. The sprite matches a rotated ellipse, which represents the surface at the point position. See figure 7. The gray circle represents the original sprite. C is the original point and $\vec{n}$ the surface normal. Additionally, to calculate the phong lighting model, the main curvatures k1 and k2 and the directions are needed. The blue ellipse represents the result pixels to draw.

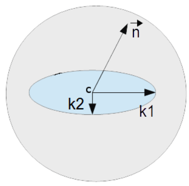


Figure 7: A single splat with the mathematical definitions

To render a large amount of points, we used an accelerating control structure. Because the input points don't move, we choose an octree implementation. The octree uses the OpenGL vertex buffer objects to send the data to the GPU. Each leaf in the tree includes a single buffer object with configurable size. If a point is added to or removed from a leaf, the octree rebuilds a single vertex buffer only. This structure is able to support frustum culling on the CPU and to reduce the workload between the main memory and the GPU memory. See figure **??** for a culling example.

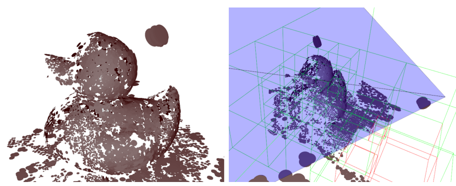


Figure 8: Left: Original camera image, right: Frustum in blue with rendered leaves in green and culled leaves in red.

Results

We used a couple of objects to validate the result of the implemented splat renderer. Figure 9 shows an elephant toy scanned with our Faro laser scanner. The point cloud includes approximately 100.000 points.

Figure 9: Representation of an elephant toy with approximately 100.000 splats.

Also the figure shows the different scanning qualities. The abdominal area doesn't contain enough points to represent the surface completely. In contrast to the head. The difference is due to the behaviour of the user. So the user can see, which area needs more input data to be complete. The performance of the algorithm depends on the number of input data, the size of the splats and the used GPU. Because the fragment shader gets the most load in the program, using a small splat size with more points is very effective. For a few points, using a large splat size can create an invalid surface representation. See figure 10.

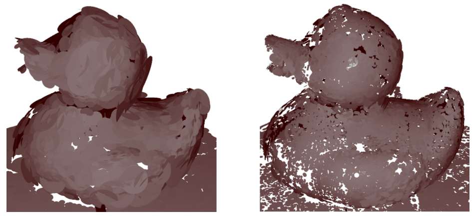


Figure 10: Representation of a duck with different number of splats and splat sizes.

Bibliography

[1] Denker, K. and Hagel, D. and Raible, J. and Umlauf, G. and Hamann, B.: On-line Reconstruction of CAD Geometry, Inter. Conf. on 3D Vision, 151-158, 2013.

[2] Mario, Botsch and Michael, Spernat and Lief, Kobbelt: Phong Splatting, Computer Graphics Group, RWTH Aachen Technical University, 2004, Presented on Eurographics Symposium on Point-Based Graphics.

Precise Characterization of the Nonlinear Spatial Transfer Function of Monitors

M. O. Franz, U. Wannek[1], F. A. Wichmann[1]

Psychophysical experiments and technical applications (e.g. in radiology or remote sensing) often require displaying images with high fidelity on a monitor. In order to assess monitor quality, one needs to measure its spatial transfer function which characterizes the linear and nonlinear interactions of neighboring pixels. In the literature, there exists no established method for measuring the nonlinear aspects of the transfer function. Here, we propose a new nonlinear method based on implicit Volterra series which – for the first time – opens up the possibility of measuring such nonlinear pixel interactions.

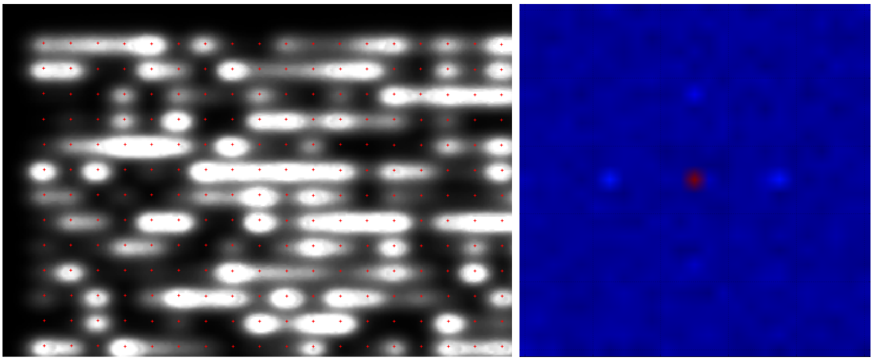


Figure 11: *Left:* Enlarged view of a CRT displaying a noise pattern. The lateral smearing of the pixels leads to strong interactions in the horizontal direction and an undesired damping of the displayed high spatial frequencies. The red dots indicate the pixel centers automatically detected by the image processing algorithm. *Right:* Second order Volterra kernel of the CRT monitor as measured by the new method. The small peaks (bright blue) around the central peak (red) indicate nonlinear interactions between neighboring pixels.

Volterra kernels are well suited for systematically characterizing linear and nonlinear interactions between neighboring monitor pixels. However, the traditional method for measuring these kernels by cross-correlation requires an excessive amount of test images which made the application of this method to measuring the spatial transfer function of monitors prohibitive. A recently developed method by one of the authors[2] estimates Volterra kernels using nonlinear polynomial kernel regression which vastly reduces the amount of required test images while achieving a much higher accuracy as compared to traditional cross-correlation. In this project, we applied the new estimation method for the first time to the spatial transfer functions of monitors.

The analysis was based on high-resolution images of the monitor surface taken with a calibrated luminance camera (see detail in Fig. 1, left). The pixel centers were automatically detected by a region counting algorithm applied to a binarized and morphologically processed version of the image. We extracted the image regions around the detected pixel centers and used them as the measured luminance output of the monitor for a given input image. This precise correspondence between input and output image allowed us to estimate the nonlinear transfer function in the form of a Volterra series. First measurements show that nonlinear pixel interactions do indeed play a role even in high quality monitors (see Fig. 1, right), thus leading to undesired nonlinear distortions in the displayed images.

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[2]Franz, M. O., and B. Schölkopf: A unifying view of Wiener and Volterra theory and polynomial kernel regression, *Neural Computation* 18(12), 3097–3118, 2006.

Radiometric calibration of digital cameras using Gaussian processes

Martin Schall, Michael Grunwald, Georg Umlauf and Matthias O. Franz

Digital cameras are subject to physical, electronic and optic effects that result in errors and noise in the image. These effects include for example a temperature depedent dark current, read noise, optical vignetting or different sensitivites of individual pixels. The task of radiometric calibration is to reduce these errors in the image and thus improve the quality of the overall application. We present an algorithm for radiometric calibration based on Gaussian Processes. Gaussian process regression is used to learn a temperature and exposure time dependent mapping from observed gray-scale values to true light intensities for each pixel. Runtime is reduced by partitioning pixels into groups and choosing one represenative pixel each while minimizing the quality reduction.

Introduction

Many scientific and industrial applications, e.g. astronomy or bioinformatics, depend on images that accurately represent the observed scene. Images taken from digital cameras with CCD or CMOS sensors are subject to a large variey of error sources. Most errors are created by the sensor noise which has four fundamental sources *photon* or *shot noise*, *Fano noise*, *fixed pattern noise* and *read noise*. These errors corrupt the measured gray-scale values of the image and are mostly dependent on the brightness of the observed scene, exposure time and sensor temperate while others are constant for any pixel.

Radiometric calibration quantifies these errors and noises. This is done individually for each camera setup in order to reduce influence on the images. Fixed pattern noise, varied sensitivites of individual pixel and vignetting can be reduced using radiometric calibration of the camera. Regression models can be used for radiometric calibration by estimating the correct intensities of the image pixels based on the observed intensities and known camera parameters. The used regression model approximates a function $f : \mathbb{R}^3 \rightarrow \mathbb{R}$ with the independent variables being the observed intensity of the pixel, exposure time and sensor temperature. The dependent variable is the correct intensity of the pixel.

Our work [2] is a machine learning approach that models arbitrary pixel characteristics dependent on exposure time and sensor temperature. The learning approach infers pixel characteristics from training examples. Gaussian processes is used for regression and is a machine learning method which can be used for extrapolation, regression and interpolation. Based on learned information, the Gaussian process can give a prediction for the relation of unseen data. Gaussian processes were chosen for regression because they adapt well to non-linear functions with added noise, as described by Rasmussen and Williams [1].

Current Status

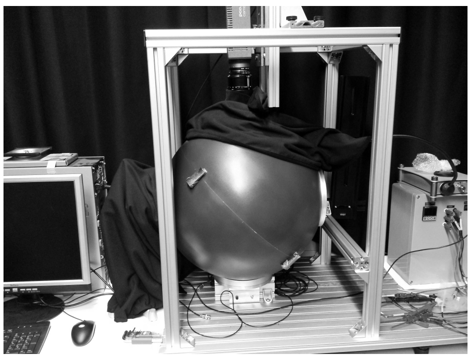

Figure 12: Hardware set-up with integrating sphere.

An important part for the work was creating training and evaluation data for the Gaussian processes. A hardware setup (shown in figure 12) consisting of an integrating sphere, digital camera, LED light source and photometer has been set up in an optical laboratory at the HTWG Konstanz. An integrating sphere in combination with the LED light source is used as a controllable, homogenous light source. Light intensity within the integrating sphere is measured by the photometer as the reference value and noisy images are taken by the digital camera that will be calibrated. A total of 200 training images were taken, evenly spaced over the specified sensor temperature range, exposure time and light intensity. The camera parameters and measured light intensities were stored together with the taken images to allow calculating the regression model from measured light intensities to true intensities.

Images were taken with a spatial resolution of $4008x2672$ pixels. Each pixel of the sensor is expected to show an individual characteristic and thus the optimal reconstruction quality can be achieved by calculating one regression model per pixel, taking the individual characteristic of each pixel into account. Since calculating a Gaussian process regression model is computationally costly, individual regression models per pixel are infeasible for high resolution images. On the other hand, calculating one regression model for the whole image would not accurately mode the individual pixel characteristics.

The chosen way to solve this is to partition the pixels of the camera sensor into partitions of equal size, each containing pixels with approximately the same characteristic. This can be done by sampling the pixel characteristics from a small number of images and lexical sorting of the pixels using the sampled characteristics as keys. In the sorted list of pixels, neighbouring ones show a identical or similar characteristic. This list is split into partitions of equal size. One pixel per partition is chosen as the representative pixel for which the regression model is calculated. In order to minimize the reconstruction error caused by partitioning, the pixel with the minimal Euclidean distance of its mean value and variance to the whole partition's mean and variance is selected as the representative pixel.

One regression model is calculated for each partitions representative pixel using the previously generated training images. Gaussian processes in function space using Gaussian radial basis functions as the covariance function are used for regression. This allows adaption to non-linear functions while prefering smooth regression functions. Radiometric calibration of the digital camera was done by estimating each pixels correct gray-value using the measured value and camera parameters as inputs for the regression function of the related representative pixel.

Using this algorithm, the runtime for calculating the regression models for a $4008x2672$ pixels image with 4000 partitions was reduced to 990 seconds using off-the-shelf hardware. Restoration of one image took 120 seconds. The mean squared error of the restored images was reduced from (depending on the use case) between 3.7% and 4.5% to between 3.1% and 3.6% of the MSE in original, uncalibrated images.

Future Work

The current implementation of this work shows that the quality of the radiometric calibration of digital cameras can be improved using regression models based on Gaussian processes. The necessary runtime for the reconstruction of one images does only allow offline applications, but no online use in industrial applications. Further research is necessary to speed up the algorithm or use more suited implementations, e.g. utilizing the GPU of the computer, for the implementation of the algorithm.

Bibliography

[1] Rasmussen, C. E. and Williams, C. K. I.: Gaussian Processes for Machine Learning (Adaptive Computation and Machine Learning), 2006.

[2] Schall, M., Grunwald, M., Umlauf G. and Franz, M. O.: Radiometric calibration of digital cameras using Gaussian processes, 2015.

The mSTAR Mission: Testing Special Relativity in Space

Thilo Schuldt, Klaus Döringshoff, Norman Gürlebeck, Sven Herrmann, Achim Peters, and Claus Braxmaier

The proposed space mission mini Space-Time Asymmetry Research (mSTAR) aims at a test of special relativity by performing a clock-clock comparison experiment in a low-Earth orbit. Using clocks with instabilies at or below the $1 \cdot 10^{-15}$ level at orbit time, the Kennedy-Thorndike coefficient will be measured with an up to two orders of magnitude higher accuracy than the current limit set by ground-based experiments. In the current baseline design, mSTAR utilizes an optical absolute frequency reference based on molecular iodine and a length-reference based on a high-finesse optical cavity. Current efforts aim at a space compatible design of the two clocks and improving the long-term stability of the cavity reference. A Phase A study has shown the feasibility of accommodating the experiment on a SaudiSat 4 bus.

Introduction

Special Relativity is classically tested by performing three types of experiments, investigating the orientation-dependence of the speed of light (Michelson-Morley experiment), the boost-dependence of the speed of light (Kennedy-Thorndike experiment) and the effect of time dilation (Ives-Stilwell experiment). The proposed mini Space-Time Asymmetry Research (mSTAR) space mission will perform a KT experiment in space by comparing an absolute (iodine-based) frequency reference to a length-based frequency reference (i.e. a laser frequency stabilized to a cavity) – both with frequency instabilities at or below the $1{\cdot}10^{-15}$ level at orbit time. This allows to determine the Kennedy-Thorndike (KT) coefficient with an up to two orders of magnitude higher accuracy than current ground-based experiments.

Performing the experiment in space offers mainly two advantages. The velocity modulation is a factor of ten higher, compared to a ground based experiment and the (putative) science signal is shifted to Fourier frequencies where the stability of oscillators is better compared to sidereal frequencies. Further, space offers a vibration free environment and elimination of large DC gravity forces.

In the baseline design, mSTAR utilizes an absolute frequency reference based on a hyperfine transition in molecular iodine near 532 nm. A frequency-doubled Nd:YAG laser is foreseen as laser that is stabilized to the iodine reference. Part of the fundamental (1064 nm) stabilized laser light is split off and sideband locked to the resonance frequency of a high finesse optical cavity made of ultra-low expansion (ULE) glass using an electro-optic modulator (EOM). This way, the frequency difference between the absolute and the length reference can be extracted from the EOM sideband frequency, which is then analyzed with respect to variations at the orbit frequency for obtaining the KT coefficient.

The mSTAR iodine clock is based on a DLR-funded setup on Engineering Model (EM) level, realized at the University of Applied Sciences (HTWG) Konstanz in cooperation with the Humboldt-University Berlin. A frequency stability below $5{\cdot}10^{-15}$ at integration times between 10 s and 5000 s was demonstrated. The length reference is based on the space-qualified cavity setup under development at JPL within the GRACE follow-on mission. A design with adapted thermal shielding required for improved long-term stability and fiber coupling to the cavity is currently realized at Stanford University.

The mSTAR mission is investigated in an international collaboration including the King Abdulaziz City for Science and Technology (KACST, Riyadh, Saudi-Arabia), Stanford University (USA), NASA Ames (USA) and a German Team consisting of the German Aerospace Center (DLR Institute of Space Systems, Bremen), the Center of Applied Space Technology and Microgravity (ZARM, University Bremen) and the Humboldt-University Berlin. In an ongoing Phase A study, the feasibility of the payload accommodation within the SaudiSat 4 satellite bus is evaluated.

Payload Overview

An overview over the mSTAR payload is given in the functional diagram shown in figure 13.

One solid-state Nd:YAG laser with a wavelength of 1064 nm is used as light source for both frequency references. The iodine reference consists of a beam preparation unit, a spectroscopy unit and corresponding locking electronics. The laser output is sent to the beam preparation unit generating pump and probe beam for the iodine spectroscopy. A secondary laser output is delivered to a modulation bench preparing the laser light for the cavity setup. As standard Pound-Drever-Hall method for cavity frequency stabilization can not be applied due to the frequency offset between the iodine and cavity resonance frequencies, an electro-optic modulator is used employing sideband locking. The feedback signal to the EOM sideband frequency is analyzed with respect to a possible KT signal at orbit frequency.

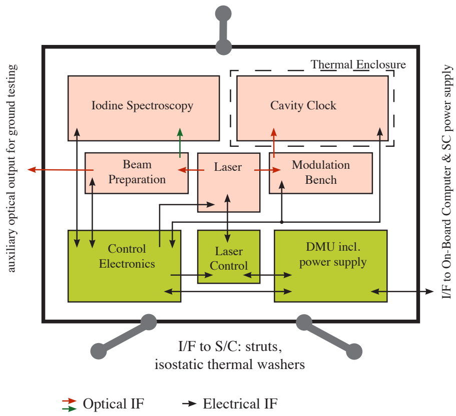

Figure 13: Functional diagram of the mSTAR payload.

The development of a space compatible iodine frequency reference setup is carried out in a cooperation of ZARM Bremen, DLR Bremen, University of Applied Sciences Konstanz, Airbus D&S Friedrichshafen and the Humboldt-University Berlin. A compact and ruggedized setup of the spectroscopy unit on engineering model (EM) level was realized, see figure 14. The optical components are joined to a fused silica baseplate using adhesive bonding technology in combination with a space-qualified two-component epoxy. This technique allows for higher long-term stability of the iodine frequency reference due to reduced pointing instability, which is a limiting effect in standard setups. The setup takes into account space mission related criteria such as compactness, MAIVT (manufacturing, assembly, integration, verification and test) and robustness with respect to shock, vibration and thermal stress. It utilizes a specifically designed multi-pass iodine cell in nine-pass configuration. The cell has dimensions of $100 \times 100 \times 30\,\mathrm{mm}^3$ resulting in an interrogation length of approximately 90 cm and utilizes a specifically designed robust cold finger design. With this setup, a frequency stability of $7 \cdot 10^{-15}$ at an integration time of 1 s and below $5 \cdot 10^{-15}$ at integration times between 10 s and 5000 s, was demonstrated in a beat measurement with a second laboratory setup of an iodine frequency reference. This frequency stability is similar to the one of the best current state-of-the-art laboratory setup of an iodine-based frequency reference [1].

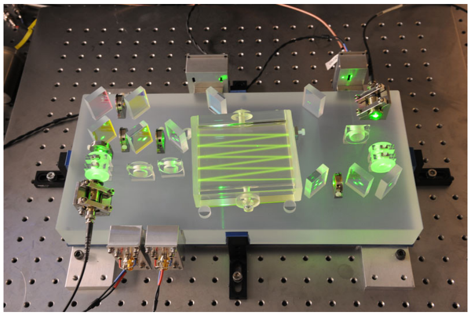

Figure 14: Photograph of the iodine spectroscopy setup.

The mSTAR baseline design for the cavity-based frequency reference foresees a mid-plane mounted cavity with a finesse $>$ 160.000 made of ultra-low expansion (ULE) glass with a coefficient of thermal expansion (CTE) of $\sim 10^{-9}$/K within an operating temperature range of 10 – 30°C and a CTE zero crossing near 15°C. By operating the cavity close to the CTE null, the effective CTE can be further decreased. Mirror substrates are made of fused silica in order to reduce thermal noise and ULE compensation rings are foreseen in order to maintain the CTE zero crossing temperature. The thermal enclosure consists of 4 gold coated aluminum cans with titanium alloy supports. Thermal simulations yield to an attenuation factor $> 10^{10}$, so that a 1 K temperature swing at the outer shield will have negligible stress effect on the cavity.

Bibliography

[1] T. Schuldt et al.: An Ultra-Stable Optical Frequency Reference for Space, Proceedings of the 10th International Conference on Space Optics (2014)