Computational Understanding of Multiple Images

Project Program: Reactive LTR Project 21914–CUMULI

1 Objectives

Automated 3D measurement and model building are key technologies for precision engineering. Digital photogrammetry — 3D measurement from sequences of digital 'photographs' — has many advantages over competing technologies: it is non-invasive, fast, and allows very large working volumes, the equipment is inexpensive, robust, portable and easy to use, and there is a strong potential for full automation. European companies — including the two industrial partners of CUMULI — are world leaders in this rapidly evolving field. However, strategic research is needed to further enhance the automation and flexibility of their products. Key areas include: (*i*) More complex scene primitives (lines, circles, facets…) — current systems measure only isolated points. (*ii*) Robust extraction and tracking of primitives through multiple images. (*iii*) Ability to incorporate and reason with known geometric constraints: *matching constraints* between structure in several images; *camera calibration* (when available); and *known 3D structure* (coplanarity, known angles or distances…). (*iv*) Improved statistical modelling and computational schemes.

There has recently been an intense and very fruitful wave of research on these and related aspects of multi-image perception, lead by the European computer vision community. The academic partners of CUMULI were actively involved in the ESPRIT projects BRA VIVA and REALISE, which lead to a significant improvement in our understanding of the geometry and invariants of multiple views, and techniques for reasoning with them. CUMULI aims to capitalize on this basic research, refining and extending existing results on multi-image geometry and reasoning, and converting them to valuable industrial know-how.

The principal objectives of CUMULI, the proposed yardsticks to measure their achievement, and the related work tasks and deliverables, are listed below. The academic partners will concentrate mainly on (1)–(3), the industrial partners on (4), but all partners will participate in a strong communal effort to develop and transfer applicable technology.

1) Extend and refine current results on multiple image geometry, reconstruction and non-point-like primitives. The key to building better measurement systems is a clearer understanding of the geometric foundations of multi-camera imaging and reconstruction. Current results are mainly limited to point-like primitives in 2–3 images (*c.f.* BRA VIVA, task 2.2). One of the major challenges is to obtain much more complete algebraic and geometric characterizations of invariant structures for extended primitives (lines, conics, spline curves…) in the general n-image case, for both discrete and continuous images. The situation is complex and powerful mathematical tools from invariant theory, algebraic geometry, tensor calculus and computer algebra will be needed. The main goal is to understand how to extract 3D geometry from images in a principled way, in both projective and Euclidean frames. This will suggest new reconstruction algorithms, and allow better theoretical analyses of stability and precision.

The research components of work tasks 1.1, 1.2, 1.3, 2.1 and 2.2 will address this major scientific objective. The main yardstick is the publication of scientific papers: those included in deliverables 1.1/12, 1.1/24 and 2.1/24, 1.2/24, 1.2/30 and 2.2/30, 2.1/12, and 2.2/24 will provide evidence for this.

2) Derive an image-based measurement framework that incorporates geometric knowledge in a symbolic form. For advanced applications it is not enough to simply measure the scene geometry: one must be able to *reason* with it, *make decisions* based on it, and *integrate* it with prior knowledge about the camera and the scene. Typical hypotheses might be alignment, parallelism or coplanarity: obviously critical properties for industrial end-users. Representations such as Grassmann-Cayley algebra are very powerful in this respect, as they can be implemented on top of conventional symbolic algebra packages, but allow formal theorems about geometric structures (points, lines, planes, cameras) to be proved automatically. These tools have been introduced into computer vision only very recently, but have already allowed the derivation of important theoretical results on multi-camera geometry.

CUMULI will develop computational tools based on these representations, that will allow camera, scene and image elements and the relations between them to be modelled as formal algebraic structures. The tools will allow us to derive closed-form solutions to geometric problems, to maintain geometric consistency in the derivations, and to infer geometric properties of the sensed data. Two particular cases that will be considered are when some camera parameter is known (*e.g.* the aspect ratio), and when one has some explicit knowledge about the 3D world (*e.g.* that some lines are parallel).

Work tasks 3.1 and 3.2 are devoted to this scientific objective, whose achievement should be measured by (*i*) scientific papers (deliverables 3.2/24, 3.2/36) and (*ii*) demonstration of the developed system (deliverables 3.1/18, 3.2/30).

3) Develop efficient, robust and accurate computational schemes based on this theory. The tools mentioned above are algebraic, providing closed form solutions from the minimum amount of data. In applications it is essential to have stable, fast numerical methods that can handle redundant, noisy, occasionally erroneous data. The development of such methods is an integral part of the project. Particular attention will be paid to implementation issues critical to the practical success of projective and Euclidean reconstruction algorithms: (*i*) the choice of parameterization; (*ii*) initialization; (*iii*) the impact of noise and outliers; (*iv*) stability and convergence properties; and (*v*) the tradeoff between parameterization, computational cost, robustness and precision. Incremental (recursive filtering) methods will be explored: these demand the choice of appropriately (de-)coupled parameterizations, *e.g.* depth and shape might be estimated separately or simultaneously. The precision and robustness of the different methods will be studied both theoretically and experimentally, using simulated and real data.

All of the scientific work tasks will contribute to this objective, but tasks 1.3, 2.1 and 2.2 are particularly relevant. The results will be used by the technology demonstrator tasks 1.4, 2.3 and 3.2. The principal yardsticks for progress are the performance and applicability of the implemented algorithms contained in deliverables 1.1/12, 1.1/24, 1.2/24, 1.2/30, 1.3/18, 2.1/12, 2.1/24, 2.2/24, 2.2/30, 2.3/24, and 3.1/18.

4) Develop advanced prototypes of systems for 3D measurement and modelling from image data. A primary goal of CUMULI is the development and transfer of industrially relevant technology. To ensure this, the scientific work is closely linked to three technology development tasks. For each of these, a working demonstrator will be provided at the end of the project. Task 1.4 led by IMETRIC concerns precise estimation of camera pose and 3D measurement using non-point-like features (lines, circles, planarity) in several images. Task 2.3 led by INNOVATIV VISION develops robust automatic on-line camera calibration and 3D motion estimation from image streams. These tasks are directed specifically at the needs of the industrial partners, and focus on developing and transferring capabilities that they feel would significantly increase their technical competitiveness. Task 3.2 led by FRAUNHOFER-IGD will develop a system for automated 3D model acquisition from image data. The geometric reasoning and modelling capabilities explored will play a key role in future industrial measurement systems.

The principal yardsticks for this objective are: (*i*) the development and implantation of expertise applicable to real-world measurement problems; (*ii*) the development of good scientific-industrial working relationships that will strengthen future R & D work. These goals are difficult to quantify, but they will be reflected in the technology demonstrators, deliverables 1.4/36, 2.3/36 and 3.2/30.

2 Work plan

Overall Structure

CUMULI is divided into four work packages: three major scientific and technological development ones, and a management and information dissemination package. To ensure a strong current of industrially relevant development and transfer, the scientific and technological aspects are closely integrated. Each development package centres on a scientific theme linked to the needs of one type of industrial application, and each has a technology demonstrator as its main final deliverable.

• Work package 1 on 3D Measurement from Discrete Images is especially relevant to the precise 3D measurement of static scenes performed by IMETRIC.

• Work package 2 on Image Streams and 3D Motion is directed at INNOVATIV VISION's motion estimation applications, especially the car crash-testing application where several independent non-rigid motions must be reconstructed from multiple image streams.

• Work package 3 on 3D-2D Reasoning will develop methods for semi-automatically reasoning with image data and building and refining 3D scene models from it. The demonstrator will build models for FRAUNHOFER-IGD's virtual reality applications, but in the longer term such reasoning and model building capabilities will become an integral part of mainstream industrial measurement systems.

Each of these work packages combines theoretical aspects, studies of uncertainty and robustness, the development of practical algorithms, and their integration into complete demonstrator systems. As a complement to the above technology transfer within the consortium, there is a small separate work task dedicated to wider industrial dissemination of the results of CUMULI.

Work Packages: Each development package is coordinated jointly by an academic package leader and an applications-directed co-leader, and each is subdivided into several tasks. Each task has its own milestones and deliverables. The package leaders are responsible for the smooth running of their task and for ensuring that its goals and milestones are met, while the co-leaders are responsible for overseeing the technology transfer process and the integration of the technology demonstrators. However, all involved partners will contribute actively to these goals.

Main Phases: Work packages 1 and 2 contain tasks explicitly dedicated to industrial transfer, while in work package 3 the transfer is distributed over the two tasks. The WP 1 and 2 transfer tasks run the entire length of the project, while the scientific tasks are somewhat shorter so as to concentrate research energy at each phase of the project. During the first six months, the transfer tasks will compare real industrial needs with the industrial and academic states of the art in each domain. The result of this will be a set of concise plans of action for strategic technology development and transfer during the project, to be delivered at month 6. This effort will include the development of target specifications for the demonstrator systems, and the supply of appropriate test data by the industrial partners. Work on the demonstrators will build up throughout the project, and the last six months will be devoted exclusively to collaborative work on them.

Milestones and Deliverables: Each work task has its own specific milestones and deliverables. The deliverables are research papers and implemented algorithms for the scientific tasks, and test data, specifications, and working demonstrators for the technology transfer tasks.

Risks: Given its strong industrial element and the fact that it will leverage off existing scientific results (*e.g.* from BRA VIVA and REALISE), CUMULI should start quickly and be very well focused, so there does not seem to be a significant risk that it will fail completely. The main risk is perhaps that the methods developed will work, but not prove to be immediately commercially viable. We think that this is more likely to happen for business reasons (*e.g.* cost and expected pay-back of a full scale, industrially validated implementation) than for technical ones (speed, complexity, robustness, of the underlying algorithms…). However the field of optical measurement is developing rapidly and the industrial partners are committed to technical excellence, so even if this happened in the short term, it is likely that CUMULI would still benefit the industry in the longer term.

Another possible problem is the difficulty of the mathematical techniques required for the theory of multi-image measurement. It took the academic partners some time to fully assimilate these, and it remains to be seen whether there will be sufficient time during CUMULI for the industrial partners to do likewise. However, even though the theory is abstract, many of the resulting algorithms are likely to be comparatively simple, so it should be possible to fall back on a 'cookbook' approach to transfer if mathematical culture proves a problem.

Critical Paths: The structure of CUMULI is relatively parallel, so critical paths should not prove to be a problem. The aim is to develop multi-image measurement technology across a relatively broad front, so if any one task should fail, most of the others could still succeed. In each development package the transfer task depends directly on each of the scientific ones. Perhaps the most critical cross-package links are the discrete-image-to-continuous-image ones between tasks 1.1 and 2.1 and 1.2 and 2.2, but these are relatively sure of succeeding.

Tables and Charts: The appendix contains several tables and flowcharts. These describe the monthly schedule of deliverables, the dependencies between tasks, and the resources to be devoted to each task.

International Standards: We are not currently aware of any standards especially relevant to the project, but should any arise we will endeavor to conform to them. Reports and documentation will be written in English and deliverable code in portable ANSI-C. As far as possible, we will use commonly supported image and CAD data formats, but these have not yet been fixed.

WP 1: Multi-Camera Geometry, Discrete Images

Partners: Lund (leader 17MM), IMETRIC (co-leader 17MM), Grenoble (17MM), Sophia (12MM), INNOVATIV VISION (2MM)
Manpower and Duration: 65MM, months 0–36

Background

In this work package, geometric structure is derived from a discrete set of images of a static scene. No adjacency between the images is assumed, but only that they are obtained by projections from a common scene. The goal is to recover the scene geometry, and the internal calibrations and relative placements of the cameras. Such problems are met in many machine vision applications, often with various kinds of prior information added: *e.g.* 3D measurements, motion estimation, augmented reality, robotics and surveying. Hence, the results of this work package will be also be important for other parts of the project.

Application: WP1 will focus on the needs of IMETRIC, who develop systems for high precision industrial measurements by means of photogrammetric methods. These systems make use of high quality cameras, whose calibration is computed very accurately. Another characteristic of photogrammetric methods is that they use geometric tokens of known positions in the scene. These are often matched to image features by hand. In comparison, a general goal of computer vision is to carry out automatic operations with a minimum of human intervention. Precision is often sacrificed for speed. For many applications, the camera calibration is unknown or uncertain, and may vary between the images, because of *e.g.* zooming.

The scene is often unknown or poorly modeled, and matching frequently leads to complicated combinatorial problems. To trade on the relative strengths of these two complementary approaches, a transfer of techniques will take place in task 1.4. Here, an prototype industrial photogrammetric system will be developed that includes computer vision methods, aimed at automating the measurement process by means of fast estimates of the camera placements, relative or absolute.

Uncalibrated cameras, unknown scenes: The basic situation of uncalibrated camera geometry is considered in task 1.1. This has been the subject of intense activity during the last few years, *e.g.* the work in VIVA on invariant structures has played an important role. A clear understanding and an algebraic theory of the geometry of image pairs has been developed, *c.f.* [9, 19, 16]. For instance it has been shown that for uncalibrated cameras, scene reconstruction up to an unknown projective transformation is possible. This has later been extended to general sets of images, using multi-image tensors, *c.f.* [20, 13, 14], but is still an area of intense research, both theoretically and computationally.

Calibrated cameras or known scenes: In many applications additional information about the scene and/or the cameras is available. Thus one often has models for objects in the scene and/or knowledge of the cameras, for instance that they are identical, *c.f.* [7, 12, 10]. The aim of task 1.2 is to assimilate such prior information into both the algebraic theory and the algorithms for computing multi-camera geometry. Contextual information will also be considered (*e.g.* known coplanarity of features,...).

Geometric features: While tasks 1.1 and 1.2 deal with point-like features, task 1.3 considers features with internal geometric structure (lines, conics,...). The intrinsic properties of these govern the imaging process, and sometimes add very strong matching constraints that can be used for improved accuracy. The goal of task 1.3 is to further develop the algebraic and geometric understanding of this situation, and to extend it to numerical algorithms, for later use on specific problems in task 1.4 and elsewhere. Another important topic of this task is the development of precise stochastic models for the image acquisition process and for low level image processing, and of error characteristics of different feature representations, *c.f.* [1].

Task 1.1. Projective multi-camera geometry

Partners: Lund (4MM), Sophia (5MM), Grenoble (4MM), IMETRIC (1MM), INNOVATIV VISION (1MM)
Manpower and Duration: 15MM, months 0–24
Inputs: Task 1.4
Outputs: Task 1.2, 1.3, 1.4, 2.1, 3.2

This task is based on point features and uses no calibration of the cameras. For image pairs the situation is well understood, *e.g.* in terms of two different approaches developed in VIVA, one using projective geometry and the other the concept of affine shape. In the multi-image case there appear tri-, quadri-, and general multilinear constraints on matching points in the different images. The aim of this task is to achieve a complete characterization of the multi-camera geometry, algebraically as well as computationally, and thereby to get a better understanding of the uncertainties and instabilities that appear in numerical algorithms.

- **Algebra for multiple projective cameras:** Unification of the projective and affine shape approaches, relations between different parameterizations of cameras, *e.g.* P-matrices, S-matrices, trilinearities, quadrilinearities and canonic representations, multi-image analysis by affine shape, multi-image invariants. (Lund, Grenoble, Sophia).

- **Robust estimation of projective camera geometry:** Algorithms for reconstruction and motion, matching by image prediction, measures of uncertainty, impact of input noise on the reconstructed structure. (Lund, Grenoble, Sophia, Imetric, I.V.).

- **Geometric degeneracy:** Error characteristics of projective structures by means of algebraic results, identification of critical configurations that cause computational instability. (Lund, Grenoble, Sophia).

Task 1.2. Euclidean and affine multi-camera geometry

Partners: Lund (4MM), Sophia (5MM), Grenoble (4MM), IMETRIC (1MM)
Manpower and Duration: 14MM, months 6–30
Inputs: Task 1.1, 3
Outputs: Task 1.3, 1.4, 2.2, 3.2

The goal of this task is to integrate prior information about the scene and/or the cameras (*e.g.* known calibration) into theory and algorithms, using point features. One such situation is that the camera calibrations are known, and another that the cameras are known to be identical, while the scene is unknown. In this case, given enough 2D to 2D matches between the images, it has been shown that the Euclidean structure can be recovered by means of the Kruppa equations, but more has to be added to the algebraic and computational theory. If the scene contains known Euclidean structures, *e.g.* beacons of known shapes and positions, classical calibration problems are met, based on 3D to 2D matches. Here also contextual information will be exploited in theory and algorithms, *e.g.* that a number of features in the scene are coplanar.

- **Algebra of Euclidean and affine multi-image geometry:** Incorporation of Euclidean constraints into the algebra of multi-image reconstruction for identical or partially calibrated cameras, Gramian matrices and affine shape. (Lund, Grenoble, Sophia).

- **Photogrammetry and computer vision:** Comparison of methods for calibration and structure recovery. (Lund, Sophia, Grenoble, Imetric).

- **Estimation of Euclidean and affine structure:** The Kruppa equations for identical cameras, dimensional analysis of Gramians, impact of noise, improving accuracy from affine knowledge, like coplanarity, collinearity or parallelism. (Lund, Sophia, Grenoble, IMETRIC, I.V.).

Task 1.3. Geometric features

Partners: Lund (4MM), Grenoble (4MM), IMETRIC (1MM), INNOVATIV VISION (1MM)
Manpower and Duration: 10MM, months 6–36
Inputs: Task 1.1
Outputs: Task 1.2, 1.4, 2.3, 3.2

In this task, the imaging geometry is governed by features having their own intrinsic geometry, *e.g.* lines, conics and curves. Problems analogous to those in task 1.1 and task 1.2 are addressed, in projective, affine and Euclidean settings. In the projective case, multilinear constraints are known to appear also for line matches, as well as for features built up by combinations of points and lines. A unified framework for this will be searched for. A common situation in industrial environments is that more general geometric features are available, described *e.g.* by a CAD-model. Methods for 3D to 2D matching of such features will be developed, using geometric constraints.

- **Imaging of algebraic-geometric features:** Extension of multilinear constraints to line matches in multiple images, analogous problems for conics and compound features, *e.g.* combinations of points, lines and conics, Grassmann-Cayley algebra. (Lund, Grenoble).

- **Imaging of contours and curves:** Structure – motion problems for images of 3D bodies, 3D- and planar curves, and regions bounded by planar curves. (Lund, Grenoble).
- **Geometric features, their extraction and uncertainty:** Efficient parameterizations of features, measures of uncertainty, stochastic models of image acquisition and of low level image processing, outlier rejection in multiple images by geometric consistency constraints. (Lund, Grenoble, IMETRIC, I.V.).
- **Structure estimation from geometric features:** Estimation of camera positions, orientations and calibrations, global optimization methods using lots of features in a number of images, 3D-2D matching by predictions from algebraic constraints, study of tradeoff between computational cost, robustness and precision. (Lund, Grenoble, IMETRIC, I.V.).

Task 1.4: Automatic Estimation of Camera Pose

Partners: IMETRIC (14MM), Lund (5MM), Grenoble (5MM), Sophia (2MM)
Manpower and Duration: 26MM, months 0–36
Inputs: Tasks 1.1, 1.2, 1.3, 3
Outputs: demonstrator
In this task the bank of algorithms and theory built up in tasks 1.1, 1.2 and 1.3 will be applied to specific problems, originating from the demands of IMETRIC. For ease of use, their cameras are usually hand-held, making it necessary to make initial estimates of the camera positions and orientations. Currently this is done manually, while the rest of the measurement process is fully automatic. To simplify the image processing, the current system requires specially made optical targets to be attached to the object being measured. To achieve a higher degree of automation and flexibility, fast and robust algorithms to solve the initial position estimation problem will be developed, either relatively, using 'natural' object features such as straight edges and circles, or absolutely, using CAD specifications.

The goals of this task are thus to produce methods and software for:

- **Relative positions and orientations of the cameras.** Automatic estimation of camera pose from geometric features such as line segments, planar facets, circles, and general curves. (Lund, Grenoble, IMETRIC).
- **Integration of prior information about the camera and the scene.** Automatic incorporation of constraints on camera calibration(s) and known 3D information about the scene — *e.g.* derived from a CAD model of the object being measured — into the estimation of 3D Euclidean camera pose with respect to the CAD coordinate system. Reconstruction of non-point-like features (lines, circles, planar facets, curves,…). (Sophia, Lund, Grenoble, IMETRIC).
- **System integration.** Integration of the modules developed with the existing IMETRIC system. Commercial evaluation of the accuracy, robustness and practicality of the results. Demonstration of the working system. (IMETRIC, Sophia, Lund, Grenoble).

WP 1 Deliverables

Task 1.1 (months 0–24)

- **Month 12, Deliverable 1.1/12** (coordinator: Lund)
  (i) Short (conference) article on the recovery of projective multi-camera geometry by algebraic techniques.
  (ii) Trial implementations of algebraic algorithms for projective reconstruction from multiple images.

- **Month 24, Deliverable 1.1/24** (coordinator: Lund/Grenoble)
  (i) Discrete image part of an overview paper on discrete and incremental multi-camera projective reconstruction. (*c.f.* deliverable 2.1/24(i)).
  (ii) Documented implemented algorithms for projective reconstruction from discrete images.

Task 1.2 (months 6–30)

- **Month 24, Deliverable 1.2/24** (coordinator: Lund)
  (i) Short (conference) article on Euclidean reconstruction by algebraic techniques.
  (ii) Trial implementations of algebraic algorithms for Euclidean reconstruction from multiple discrete images.

- **Month 30, Deliverable 1.2/30** (coordinator: Lund/Grenoble)
  (i) Discrete image part of an overview paper on discrete and incremental multi-camera Euclidean reconstruction. (*c.f.* deliverable 2.2/30(i)).
  (ii) Documented implemented algorithms for Euclidean reconstruction.

Task 1.3 (months 6–36)

- **Month 18, Deliverable 1.3/18** (coordinator: Lund)
  Trial implementations of algorithms for estimation of camera positions from images of lines, conics and features described by CAD-models.

- **Month 36, Deliverable 1.3/36** (coordinator: Lund)
  Documented implementations of algorithms for estimation of camera positions from images of scenes, containing features described by CAD-models.

Task 1.4 (months 0–36)

- **Month 6, Deliverable 1.4/6** (coordinator: Lund/Imetric)
  (i) Report: Discrete image part of CUMULI plan of action for technology development and transfer in WP 1 and 2, including scientific *vs.* industrial state of art and specification of performance goals for demonstrator (*c.f.* deliverable 2.3/6(i)).
  (ii) Delivery of test data from IMETRIC.

- **Month 12, Deliverable 1.4/12** (coordinator: Imetric)
  Delivery of industrial data from IMETRIC.

- **Month 36, Deliverable 1.4/36** (coordinator: Imetric)
  Demonstrator from IMETRIC. This will involve a demonstration of the implemented algorithms, showing how they work and giving a practical run-through using the necessary hardware and software.

WP2: Image Streams and 3D Motion

Partners: Grenoble (leader 15MM), INNOVATIV VISION (co-leader 20MM), Lund (14MM), Sophia (11MM)
Manpower and Duration: 60MM, months 0–36

Background

This work package focuses on the estimation of 3D structure and motion from one or more continuous image streams. This is a key problem for many vision-based industrial inspection and control tasks, and also for visual interface applications such as those being developed by Fraunhofer-IGD. However, in CUMULI we will focus on precise 3D motion estimation for applications such as those of INNOVATIV VISION.

Although the underlying theoretical foundations are the same for continuous and discrete images, the style of approach and the final implementation techniques tend to be rather different. For discrete images the emphasis is on refined algebraic and statistical techniques that make the most of the limited amount of image data. For image streams the sheer volume of data makes most optimal approaches infeasible, and the emphasis is on fast but relatively coarse incremental numerical algorithms. At the same time, the structural continuity of image streams allows the token matching problem to be simplified using robust tracking and filtering (motion modelling) approaches. Current algorithms for this are usually suboptimal and rather *ad hoc*, so it is important to develop the underlying theory to the point where accurate and robust incremental tracking and reconstruction techniques can be created.

Incremental Geometry: The geometry of discrete images has recently been a subject of intensive study [7, 16, 19, 20, 13, 14], but the corresponding situation for continuous image streams is not yet well understood. Much of the geometry inherited from the discrete camera case becomes degenerate when the cameras approach one another or the inter-image motions become aligned. This is not an insurmountable problem, but it does mean that a careful study of the incremental geometry is required (*c.f.* [21, 15]), followed by the development and testing of projective calibration, matching, reconstruction, and uncertainty handling algorithms that are accurate and robust in these limiting cases. These topics are the subject of task 2.1.

Incremental Constraints: In order to obtain accurate Euclidean structure and motion estimates, incremental methodologies must also be developed for continuous camera and motion constraints. For example, cameras can be calibrated incrementally by tracking a set of known, fixed targets in the scene, and the 3D Euclidean structure of the scene can then be recovered using the calibrations. Similarly, incremental constraints on the motion — for example the hypothesis that over a certain period some group of targets moves linearly or rigidly — can be validated and incorporated into the model to obtain more accurate motion estimates. The nonlinearity of the reconstruction process makes it difficult to incorporate such incremental constraints cleanly into a general estimation framework, although some work on the corresponding discrete problem [8, 16, 11] and a number of *ad hoc* special cases exist. Task 2.2 will investigate the basic geometric structure of the most important incremental constraints for applications, and develop error models and constraint handling algorithms to allow them to be incorporated into 3D structure and motion estimates. The higher levels of the constraint handling process will be considered in work package 3 on Reasoning.

Application: Finally, in the technology transfer task 2.3 the academic partners will collaborate with INNOVATIV VISION to build a working prototype of a 3D motion estimation system, which will be demonstrated at the end of the project. In addition to the results and software developed in tasks 2.1 and 2.2, this will require a significant effort on 'low-level' image and data processing. Although this is not a basic research goal of the project, it will constitute a nontrivial contribution that is essential to allow a realistic validation of the research results. Robustness and reliability will be key concerns, and it is very likely that the methods developed will be of direct interest to the industrial partners, so that even here a significant transfer of technology can take place.

Task 2.1: Incremental Projective Camera Geometry

Partners: Grenoble (5MM), Lund (5MM), Sophia (5MM), INNOVATIV VISION (1MM)
Manpower and Duration: 16MM, months 0–24
Inputs: Task 1.1, 2.3
Outputs: Task 2.2, 2.3, 3.2

This task aims to clarify the underlying projective geometric structure of the continuous image situation. The geometry of stationary point targets in discrete images is now fairly well understood, but this needs to be extended to continuous images and moving or more general features. In this task the camera calibrations may be unknown and time-varying and structure will be recovered only up to a projectivity.

- **Incremental uncalibrated multi-camera geometry:** basic projective geometry of closely-spaced cameras; types of degeneracy, limiting cases, and series expansion in displacement parameters; incremental multilinear matching constraints and feature transfer methods for point and line tokens; incremental affine shape, tensorial, and Grassmann-Cayley algebra based approaches and their relationships. (Grenoble, Lund).

- **Incremental matching, reconstruction and transfer:** development of practical incremental token matching, projective reconstruction, and feature transfer algorithms based on the above theory. (Grenoble, Lund, I.V.).

- **Incremental uncertainty:** investigate efficient recursive methods of incorporating statistical models of measurement error into the above nonlinear framework (Grenoble, Lund).

Task 2.2: Continuous Constraints and Euclidean Structure

Partners: Grenoble (5MM), Lund (5MM), Sophia (5MM), INNOVATIV VISION (1MM)
Manpower and Duration: 16MM, months 6–30
Inputs: Task 1.2, 2.1, 2.3
Outputs: Task 2.3, 3.2

Continuity constraints lie at the very heart of continuous image measurement. This task investigates the practically most important classes of these and their relationship to the corresponding discrete-case constraints. Information about the scene (fixed known targets) or the cameras (partially calibrated, stationarity, fixed internal optics) is used to recover affine and Euclidean structure and motion.

- **Incremental calibration from scene constraints:** continuous multi-camera position, calibration, and uncertainty by tracking known 3D features; special case of correcting for film misregistration in high speed cameras (motion of principal point). (Grenoble, Lund, I.V.).

- **Incremental calibration from camera constraints:** affine and Euclidean structure from one or several fixed-calibration cameras moving or watching a moving object; special case of affine structure from fixed cameras watching a linear motion (moving car). (Grenoble, Lund).

- **Incremental Euclidean structure and motion:** continuous Euclidean reconstruction, motion and uncertainty, using the above calibration methods; incorporation of known constraints on 3D structure to improve motion estimates. (Grenoble, Lund, I.V.).

Task 2.3: On-line Calibration and 3D Motion Estimation from Image Streams

Partners: INNOVATIV VISION (18MM), Grenoble (5MM), Lund (4MM), Sophia (1MM)
Manpower and Duration: 28MM, months 0–36
Inputs: Task 2.1, 2.2, 1, 3
Outputs: demonstrator

In this task, the image-stream measurement technology developed in tasks 2.1 and 2.2 will be transferred to INNOVATIV VISION and applied to a real-world 3D motion estimation problem.

INNOVATIV VISION provides systems for the precise measurement of 3D position, orientation, velocities and accelerations using image sequences obtained from one or more cameras. In one important application, car crash tests are filmed with several high speed movie cameras, and the results are digitized to high precision and used to reconstruct the non-rigid 3D motion of the crashing car and the test dummy. This application requires the simultaneous tracking of point targets on several rapidly moving non-rigid objects, through hundreds of images in up to 20 non-synchronized cameras. The cameras are calibrated beforehand, but owing to vibrations and mechanical misregistration of the film, their effective calibrations fluctuate randomly during the sequences. To further automate the measurement system, and to provide more accurate and robust results, INNOVATIV VISION would like improve its current tracking and motion estimation processes. It would be especially useful to be able to calibrate the cameras on-line from the image data, by tracking a number of fixed, known points visible in the scene.

The academic partners will develop a set of well-engineered 'low-level' image and data processing routines for use by the higher level algorithms developed in tasks 2.1 and 2.2. The aim is to provide a reliable interface to the image data rather than to advance the current state of the art in feature extraction and tracking, but careful attention will be given to the key issues of outliers, robustness and uncertainty. INNOVATIV VISION will provide approximately calibrated high resolution digitized image sequences for software testing, and will be responsible for the operating specifications, integration, and commercial evaluation of the resulting system, using the software modules supplied by the academic partners.

In detail, this task will produce the following methods and software:

- **Robust automated point matching and tracking** through long image sequences. (I.V., Grenoble, Lund).
- **Robust automatic on-line calibration** of several non-synchronized cameras through long image sequences, based on tracking known fixed points in the environment. (Grenoble, Lund).
- **Semi-automated motion segmentation and 3D motion** (pose, velocity, acceleration) estimation for rigid, rapidly moving 3D objects. (Grenoble, Lund, I.V.).
- **Integration** of above software with the existing I.V. system. Evaluation of the accuracy, robustness and commercial viability of the results. Demonstration of the working system. (I.V., Grenoble, Lund).

WP 2 Deliverables

Task 2.1 (months 0–24)

- **Month 12, Deliverable 2.1/12** (coordinator: Grenoble)
  (i) Short (conference) article on incremental multi-camera matching and projective reconstruction (incrementalizations of matching constraints and selected projective reconstruction techniques).
  (ii) Trial implementations of incremental reconstruction algorithms.

- **Month 24, Deliverable 2.1/24** (coordinator: Grenoble/Lund)
  (i) Incremental image part of an overview paper on discrete and incremental multi-camera projective reconstruction (*c.f.* deliverable 1.1/24(i)).
  (ii) Documented implemented algorithms for incremental projective reconstruction.

Task 2.2 (months 6–30)

- **Month 24, Deliverable 2.2/24** (coordinator: Grenoble)
  (i) Short (*e.g.* conference) article on continuous Euclidean reconstruction.
  (ii) Trial implementations of Euclidean reconstruction algorithms.

- **Month 30, Deliverable 2.2/30** (coordinator: Grenoble/Lund)
  (i) Incremental image part of an overview paper on multi-camera Euclidean reconstruction (*c.f.* deliverable 1.2/30(i)).
  (ii) Final documented algorithms for incremental Euclidean reconstruction.

Task 2.3 (months 0–36)

- **Month 6, Deliverable 2.3/6** (coordinator: I.V.)
  (i) Report: Continuous image part of CUMULI plan of action for technology development and transfer in WP 1 and 2, including scientific *vs.* industrial state of art and specification of performance goals for demonstrator (*c.f.* deliverable 1.4/6(i)).
  (ii) Data set: test sequences from INNOVATIV VISION.

- **Month 24, Deliverable 2.3/24** (coordinator: Grenoble)
  Software library: robust feature tracking and motion segmentation, for use in demonstrator.

- **Month 36, Deliverable 2.3/36** (coordinator: I.V.)
  Demonstration: INNOVATIV VISION system working on real industrial data. (Video, or live demo if requested).

WP3: Algebraic Symbolic Reasoning

Partners: Sophia (leader 24MM), Fraunhofer-IGD (co-leader 22MM), Lund (7MM), Grenoble (3MM)
Manpower and Duration: 56MM, Months 0-36
Inputs: WP 1 and 2, results of Realise

This work package investigates the possibility of using automatic geometric reasoning to aid the construction and management of large geometric data bases such as those obtained, for example, in the EC BRA project 8878 REALISE in which two of the partners (Fraunhofer-IGD and Sophia) are involved. The target application is the development of a more powerful system than the one developed in REALISE that incorporates automatic reasoning to help further the task of 3D geometric modelling from images.

Research in mathematics has now reached the point where it is possible to use existing systems for symbolic algebra such as MAPLE or MACAULEY as a basis for building systems capable of automatically inferring geometric theorems.

In this proposal we are concerned with theorems of geometry in two and three dimensions which we view as properties of the images or the environment. For example, when building a CAD model of a building from photographs, the fact that some corresponding image lines intersect at a single point in all images is an indication that the corresponding 3-D lines may be parallel. These properties are simple examples of so-called *incidence* properties which can be manipulated symbolically.

A major difference between our context and the usual mathematical one is that we want to do symbolic manipulation with uncertain data: image measurements and the resulting 3-D reconstructions are noisy and this must be taken into account in the development of the theory and its applications.

We first give a quick overview of two symbolic tools which we think are well adapted for geometric theorem proving in 2D and 3D spaces.

The first method [18, 17] deals with projective geometry and incidence relations. The environment for this approach is the exterior algebra of the space $\mathbf{E}$, where the points live. This approach generalizes the Cayley operators, introduced by Rota [6]. In the exterior algebra, two operators "meet" and "joint" describe the intersection and sum of linear spaces, when this intersection is generic. In the non-generic cases, for instance when we want to deal with intersection of lines in a 3-D space, we need to extend these operators, to treat all possible cases of intersection of two linear spaces. The objects manipulated at this stage, are linear combinations of exterior products of points, whose coefficients are polynomials in determinants of points. Such objects are independent of the referential, the coefficients being invariant quantities. In order to test a geometric property for a given configuration of points $A_1, \dots A_k$, the method proceeds as follows. We construct by induction rewriting rules on $A_1, \dots, A_k$, which reduce to zero any geometric property valid in the non-degenerated cases. Moreover, the unique (in the case of incidence relations) generic component is characterized by the dimension of its projection on the subspaces corresponding to $(A_1, \dots, A_k)$.

The second method, developed by Wu [24] and others [5, 23], is based on algebra on polynomials in a referential. The hypotheses correspond to polynomials in the coordinates of the points, treated as variables. The algorithm transforms the system of hypothesis into a triangular form where each new equation introduces a new variable. To test a geometric property of a configuration, the polynomial(s) corresponding to this property are reduced by pseudo-remainders with respect to the triangular sets of polynomials. If the remainder is zero, the property is true on the component associated with the triangular system. Degenerate components are avoided by introducing free parameters, among which no algebraic relations are allowed. This method is based on the notion of characteristic sets and requires factorization tests in quotient algebras by the previous polynomials. In the case where the polynomials are of degree two or less (most of the cases in simple geometric theorem proving), this problem can be easily handled by simple tools. For geometric problems where polynomials of degree 3 appear, more sophisticated machinery is necessary [22].

This method has recently been generalized [4]; instead of dealing with polynomials corresponding to the direct translation of the hypotheses, one uses intrinsic quantities such as determinants and scalar products. In this case, the reduction is done by introducing parameters and doing direct reduction on the points and the geometric quantities that appear in the formula. In some sense, it mixes the two previous approaches by using both invariants and algebra.

We believe that the formalism used in the previous three approaches can be generalized in order to manipulate more easily configurations of points, lines, planes, and perhaps other geometric primitives such as spheres in a homogeneous and synthetic way.

The applications of such a system that we will investigate in this project are fivefold:

Maintain the coherence of the geometric data base

In a partially interactive scheme such as the one developed in Realise, the user proposes geometric properties of the environment that he models, e.g. that some lines are coplanar. It is important to test whether this does not introduce any contradiction with previous geometric facts already known by the system. This can be done automatically using the previous tools since from an algebraic point of view, it consists in testing with the corresponding polynomial system, if the degree of freedom of each point (i.e. the dimension of some projections) is correct. This feature would be extremely useful also in the context of uncertain image and 3-D measurements where several hypotheses must routinely be tested.

Predict properties of the environment

The same tools could also be used to test if some simple geometric properties, e.g. incidence properties such as alignment, coplanarity, ..., are true or not. In our algebraic framework, this is equivalent to generating all "theorems" of a certain class. The problem of generating all theorems i.e. all properties of the environment is much more difficult because it implies the ability to eliminate some variables (a costly algebraic process) and then to be able to interpret the (usually very big) formulae that result from this elimination. However, we think that some steps in this direction can be taken.

Update the uncertainty

We mentioned several times the important fact that the reconstructed 3-D geometric primitives have some uncertainty attached to them. This uncertainty must be coherent with the geometric properties verified by the primitives. For example if some points are aligned, this geometric property is represented symbolically in the geometric data base but it should also be reflected in the representation of the uncertainty of the points.

The problem of propagating the uncertainty from image measurements to calibration and reconstructed data is addressed in work packages 1 and 2. In this work package we will investigate how this uncertainty can be further reduced by taking into account higher-order geometric properties such as the above mentioned "theorems". This problem is not new and has already received considerable attention [3]. Hypotheses of geometric properties (e.g. these points are coplanar) can be weighted according to the uncertainty of the primitives which participate in the hypotheses. Mechanisms for computing these weights are well known [2]. What is much less well-known is how to incorporate this high level of uncertainty propagation into an automated symbolic reasoning system.

Help the correspondence process

Obtaining feature correspondences between a large number of images (say more than two) is admittedly a very difficult task because of such things as noise, occlusion and perspective distortion. We believe that a geometric reasoning system capable of manipulating three dimensional concepts in a symbolic manner can play an important role in increasing significantly the number of matched primitives across views, resulting in improved performances.

Scene modelling

These functionalities will be integrated, in particular through the close collaboration with the Fraunhofer-IGD partner, into a vision-based modelling tool which will itself be embedded into a scene modelling system. We will start with the system delivered by the Realise project which contains none of the above features and will improve it incrementally using the techniques developed in WP1, WP2 and the ideas of this WP. One of the main goals in this process is to automate modelling tasks as much as possible through computer vision support. Thus, the user will be able to construct a 3D-model of a real scene for Virtual Reality of animation purposes, by exploiting real image sequences with the help of powerful computer vision and automatic geometric reasoning tools.

The work package is broken down into two tasks.

Task 3.1: Development of a system for geometric theorem proving in two and three dimensions

Partners: Sophia (leader 12MM), Fraunhofer-IGD (11MM), Lund (4MM), Grenoble (2MM)
Manpower and Duration: 29MM, 0–18

This task aims at developing a system for geometric theorem proving which can be used in such applications as the modelling of three-dimensional environments containing mostly man-made objects from images. A number of systems with some of the required capabilities already exist [18, 17, 5, 4] but are limited in various ways. The first system [5] cannot cope well with polynomials of degree larger than two which severely restricts its range of application, the second system [4] is limited to 2-D geometry whereas we need 3-D geometry, and the third one [17] is limited to pure projective incidence relations whereas we need affine and Euclidean relations.

The first 6 months of the task will be dedicated to a thorough analysis and testing of existing systems in view of their possible application in vision-based modelling, together with a specification of the system required for solving the target application, of the language of implementation, and of its interface with the vision-based modelling system. A very important point will be to investigate how the notion of uncertainty can be taken into account.

The next twelve months will be dedicated to the development of the system itself.

Task 3.2: Application of geometric theorem proving to vision-based modelling of real scenes

Partners: Fraunhofer-IGD (11MM), Sophia (12MM), Lund (3MM), Grenoble (1MM)
Manpower and Duration: 27MM, months 12–36

The last twenty-four months of the work package will be devoted to the extensive testing and improvement of the system in conjunction with the vision-based modelling system developed within the project Realise in order to analyze its impact on the five previously mentioned problems:

1. Maintain the coherence of the geometric data base (Sophia, Lund).
2. Predict properties of the environment (Sophia, Lund) .
3. Maintain the coherence between the geometric data base and the representation of the uncertainty (Sophia, Lund).
4. Help the correspondence process (Sophia, Lund).
5. Improve the vision-based modelling tool and its connected scene modelling system (Fraunhofer-IGD, Sophia).

It is foreseen that through this testing, the initial system will be modified and improved.

Fraunhofer-IGD is currently involved in the development of several industrial VR-applications (e.g., VR walk-throughs for architectural applications, cyber-cities and virtual prototyping). One of the major difficulties in these projects is the 3D modelling task and the creation of virtual scenes. Very often, virtual objects need to be presented in existing environments. A typical scenario is: "how will my new house look in the existing street", or "how will the new interior design look in the existing architecture". Therefore, 3D models of existing objects need to be generated. Conventional modelling techniques are very inefficient for this task: the acquisition of the necessary data (in the form of land register data or 2D architectural drawings) is very time consuming; and the data itself is usually incomplete or just unavailable. On the other hand, a video sequence of the existing environment is very easy to acquire.

In this task, Fraunhofer-IGD will apply the advanced version of the vision-based modelling tool in industrial projects (e.g., in the area of architecture, interior design or cyber-city) for the generation of a 3D VR-model. To fulfill this task, steps in the modelling process need to be identified, which can benefit from or be replaced by vision-based modelling. Finally, we will develop processing methods that efficiently apply conventional modelling and the newly developed vision based modelling to industrial projects. We think that this is very important in order to demonstrate the efficiency of the new technology and to transfer the new results to related industrial projects.

WP 3 Deliverables

Task 3.1 (months 0-18)

Month 18, Deliverable 3.1/18 (leader: Sophia)
Demonstration of the prototype software.

Task 3.2 (months 12-36)

Month 24, Deliverable 3.2/24 (leader: Sophia)
Draft of a publication (ready for submission) on the use of automatic geometric reasoning for maintaining the coherence of the geometric data base and for predicting properties of the environment

Month 30, Deliverable 3.2/30 (leader: Fraunhofer)
Demonstration of a modelling system incorporating some of the features developed in task 3.1

Month 36, Deliverable 3.2/36 (leader: Sophia)
Draft of a publication (ready for submission) on the use of automatic geometric reasoning for maintaining the coherence between the geometric data base and the representation of the uncertainty for helping the correspondence process.

WP4: Management and Wider Dissemination of Results

Task 4.1: Management

The management work task 4.1 is discussed fully in the section on management below.

Task 4.2: Wider Dissemination of Results

Partners: all partners (coordinator: Grenoble)
Manpower and Duration: 5.5MM, months 0–36

The main mechanism for exploiting the results of CUMULI is direct transfer of know-how and implemented algorithms from the academic to the industrial partners. This is handled in three dedicated technology development tasks, each focused on the needs of one application domain and tightly integrated with one scientific work package. Task 1.4 considers Automatic Estimation of Camera Pose for IMETRIC, task 2.3 examines On-line Calibration and 3D Motion Estimation from Image Streams for INNOVATIV VISION, and task 3.2 studies Automated Geometric Model Building from Visual Data with FRAUNHOFER-IGD.

These transfer tasks will assure strong technology take up within the CUMULI consortium, but to complement this a small work task has been devoted to external take up and the wider dissemination of results. Our strategy focuses on three dissemination mechanisms: (*i*) industry workshops; (*ii*) CUMULI presence at trade fairs; (*iii*) world wide web pages. In addition, the traditional scientific and industrial channels will be used: scientific seminars, conference and journal papers; and industrial displays at trade fairs, advertising and technical brochures detailing new products developed. Each of the industrial partners is in contact with a wide range of European and international end-users, who will directly benefit from the improved measurement technology that CUMULI provides.

Industry Workshops: Highly focused industry workshops are a very effective means of informing industrial end users of the potential of new technologies. We feel that such workshops are best handled nationally rather than at the European level. This significantly reduces travel times and costs so that more people are able to attend, and it also allows the presentations to be precisely tailored to national needs (language, types of industries and applications,…) so that much stronger person-to-person interaction is possible.

We are actively investigating the possibility of organizing several national-level industry workshops on CUMULI-related topics. These will be held under the sponsorship of national scientific or engineering organizations. In France there was a very successful Paris meeting on precise measurement of image features several years ago, in which both INRIA and IMETRIC participated. This was sponsored by the national French research programme GDR-PRC, and we understand that a follow-on workshop on a similar topic would be very welcome. In Sweden it seems likely that such a workshop could be held in conjunction with the annual meeting of the Swedish Society for Automated Image Analysis (SSAB). Typically about 100 people attend these meetings, of whom about one third come from industry. We are looking into the possibility of holding similar workshops in other European countries.

Presence at Trade Fairs: INRIA and FRAUNHOFER-IGD regularly organize and participate in large industry fairs such as CeBIT, and these are excellent vehicles for the dissemination of the ideas developed in CUMULI. The industrial partners will emphasize the combined industrial and academic R & D strength behind their products by including displays about CUMULI on their stands at trade fairs, with contact addresses and pointers to further literature. The consortium is also willing to participate in any relevant EC IT trade fairs or industry seminars that may occur. Professional displays describing the industrial relevance of CUMULI will be produced for these purposes.

World Wide Web Page: For the widest possible publicity, there will be a CUMULI World Wide Web page containing a project description and pointers to further information and contact points. The provisional address is http://www.inrialpes.fr/CUMULI.

WT 4.2 Deliverables

- **Month 6, Deliverable 4.2/6** (coordinator: Grenoble)
  The web page will be active at the latest by month 6 of CUMULI, and will be updated as necessary throughout the project. (There will be no associated formal paper deliverable).

- **Month 36, Deliverable 4.2/36** (coordinator: Grenoble)
  A short (<5 page) report on the national-level industrial workshops held or scheduled, with a list of trade fairs with CUMULI displays and other dissemination efforts, will be included in the CUMULI final report (deliverable 4.1/36).

3 Management

Partners: all partners (coordinator: Grenoble)
Manpower and Duration: 19.5MM, months 0–36

Coordinator: INRIA Grenoble will act as overall coordinating partner for CUMULI, but to distribute the burden of management as much as possible, each work package will have a separate academic leader and applications-oriented co-leader (see below).

Project Management Committee: Overall responsibility for all strategic decisions, financial and contractual issues, conflict resolution and other project-wide activities will be jointly held by a **Project Man-**

agement Committee (PMC). This will contain the Project Leader (see below) and one voting representative from each partner. The Project Leader will serve as non-voting chairman, but will have the deciding vote in the event of a tie. The representatives will be the managers of the project at each site, or their nominated deputies. Each representative will be responsible for providing cost and administrative information for his site to the PMC, and implementing the PMC's consensus decisions at his site. The PMC's main functions are:

- establishing the Consortium Agreement and the terms of the contract with the CEC;
- managing the project, deciding on ranging options and reviewing or amending the work program;
- laying down procedures for project publications and press releases;
- resolving any disputes that may arise.

Consensus will be sought on all problems and major decisions.

Project Leader: The coordinating partner will appoint a **Project Leader** to serve as official contact and technical coordinator for the project. He will be responsible for:

- maintaining contact with the Commission and the individual partners' project leaders;
- overseeing the execution of the contract and all technical activities of the project;
- monitoring progress against the planned objectives, schedule and budget, and interaction between the partners, and proposing any needed actions and replannings to the PMC;
- overseeing (collecting, editing, reviewing,...) the preparation of all due cost statements, progress reports, project deliverables, and technical publications, and transmitting them to the CEC;

Package (Co-)Leader: For each work package, an academic partner has been designated **Package Leader** and an applications-oriented one **Package Co-Leader**. The Leaders will supervise and coordinate the activities of their packages, interacting closely with the partners involved and the Project Leader. The Co-Leaders will be specifically responsible for the industrial orientation and take-up of results in the package. Leaders and Co-Leaders will normally be the PMC members from their sites.

Meetings: Management meetings will usually be held by telephone to reduce cost and save time. Both task level and general meetings are planned. Formal meetings among members of work packages or tasks will be held as needed, according to a detailed pre-agreed agenda. They will be chaired by the package leader, who is responsible for preparing and distributing the agenda and minutes and summarizing progress to the PMC.

General meetings of the PMC together with the project leader will be held every three months. The agenda and minutes will be prepared by the project leader. Both technical and administrative issues will be discussed. At each meeting, the leader of each active work package will make a brief presentation to the PMC, concentrating on progress and achievements in the period under review and on work planned for the next review period. Internal costs and progress for each partner will be monitored by the corresponding PMC member. If significant deviations from agreed schedules are detected, these must be pointed out to the PMC and discussed at the next general meeting. The exploitation managers of the industrial partners will participate at least in the 6 monthly PMC meetings, to coordinate the strategy for exploitation of results with technical progress. If necessary, additional PMC meetings may be called by any partner at any time.

Roger Mohr from Grenoble will act as Project Leader. The PMC members will be as follows:

Site	PMC Member	Phone	FAX	E-mail
	Roger Mohr	+33 76615225	+33 76615252	Roger.Mohr@inrialpes.fr
Grenoble	Bill Triggs	+33 76615233	+33 76615252	Bill.Triggs@inrialpes.fr
Sophia	Olivier Faugeras	+33 93657831	+33 93657765	Olivier.Faugeras@inria.fr
Lund	Gunnar Sparr	+46 46 2228528	+46 46 2224010	gunnar@maths.lth.se
FRAUNHOFER	Stefan Mueller	+49 6151 155188	+49 6151 155199	stefanm@igd.fhg.de
INNOVATIV VIS	Anders Kalldahl		+46 13214897	Anders_Kalldahl@ivab.se
IMETRIC	Horst Beyer	+41 66659365	+41 66659360	imetric@dial.eunet.ch

Deliverables: As specified in article 10 of annexe II of the contract, the management deliverables will be two annual Periodic Progress Reports (deliverables 4.1/12, and 4.1/24) and the CUMULI Final Report (deliverable 4.1/36). Each of these will contain an administrative section (progress, resources used, alterations to the work plan), and a results section suitable for distribution to potential end-users of the results of CUMULI or publication by the CEC. The final report will also include as annexes: (*i*) a technology implementation plan coordinated by the industrial partners, detailing all foreground rights, exploitation intentions and timetables, and plans for the promotion of background technology; (*ii*) a report on workshops and other dissemination efforts (deliverable 4.2/36).

4 Take Up of Results

Direct Technology Transfer: The most important mechanism for exploiting the results of CUMULI is the direct transfer of technology to the industrial partners. CUMULI is fortunate in having two active, technically proficient, and highly focused industrial partners who are directly interested in the theory and techniques being developed.

1) Each applications-oriented partner is responsible for setting the goals and verifying the successful completion of a technology transfer work task specifically dedicated to its own application area and directly linked to one of the scientific work packages: IMETRIC, task 1.4; INNOVATIV VISION, task 2.3; FRAUNHOFER-IGD, task 3.2.

2) Towards the end of the project, the new techniques developed will be incorporated into working prototypes of industrial applications and validated under industrial conditions (deliverables 1.4/36, 2.3/36 and 3.2/30). From there, the results will feed directly through into the industrial partners' product lines.

3) The industrial partners will also act as observers in the scientific tasks most directly relevant to them, and as consultants to the consortium in their own specific areas of expertise.

Hence, a very tight industrial-academic collaboration and a strong transfer of relevant know-how is assured. Accurate 3D measurement is a key technology for precision engineering, and the industrial partners are suppliers of consultancy, software, and complete turnkey systems to a wide range of mainstream European industries, so the new measurement techniques developed by CUMULI will directly benefit European industry as a whole.

Public Awareness: To complement the internal take up mechanisms within CUMULI, and to ensure the widest possible distribution of the results, a small work task (4.2) has been devoted to wider information dissemination. The results will be publicized through the usual academic and commercial channels, at major trade fairs (*e.g.* CeBIT), and on the Internet (http://www.inrialpes.fr/CUMULI). We are also investigating the possibility of holding highly focused national-level industry workshops on CUMULI-related topics, as we feel that these are the best means of informing potential users of the new technology and getting feedback on their real needs (*c.f.* task 4.2).

5 Reports, Deliverables and Reviews

Reports: Reports will be issued as specified by article 10 of annex II of the contract. There will be two annual Periodic Progress Reports (deliverables 4.1/12 and 4.1/24) and the CUMULI Final Report (4.1/36). These will contain current status, administrative information and publishable summaries of current results suitable for distribution to potential end-users of CUMULI technology. The final report will also contain a technology implementation plan and a report on wider dissemination efforts (deliverable 4.2/36). Refer to the paragraph on management deliverables on page 19 for details.

There will also be a joint 'system specification and plan of action' report for work packages 1 and 2 at month 6 (deliverables 1.4/6(i) and 2.3/6(i)).

Deliverables: Each work task has its own deliverables, as described in section 2, table 1 and form 5.1.

Reviews: Unless the Commission requests otherwise, reviews will be held annually at the end of months 12, 24, and 36 of the contract. The locations for the reviews are not yet fixed.

6 Obligations & Rights of Participants

At present, we feel that the provisions on the rights and obligations of partners in the standard contract will suffice for CUMULI.

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Appendix: Tables and Charts

Figure 1 shows the period of each work task and the corresponding milestones and deliverables, and figure 2 illustrates the main dependencies between tasks and the most critical deliverables in the development work packages 1–3. The dissemination task 4.2 depends on all of these. Table 1 shows the number of man months to be devoted to each work package and task at each site, and table 2 lists the monthly schedule of deliverables.

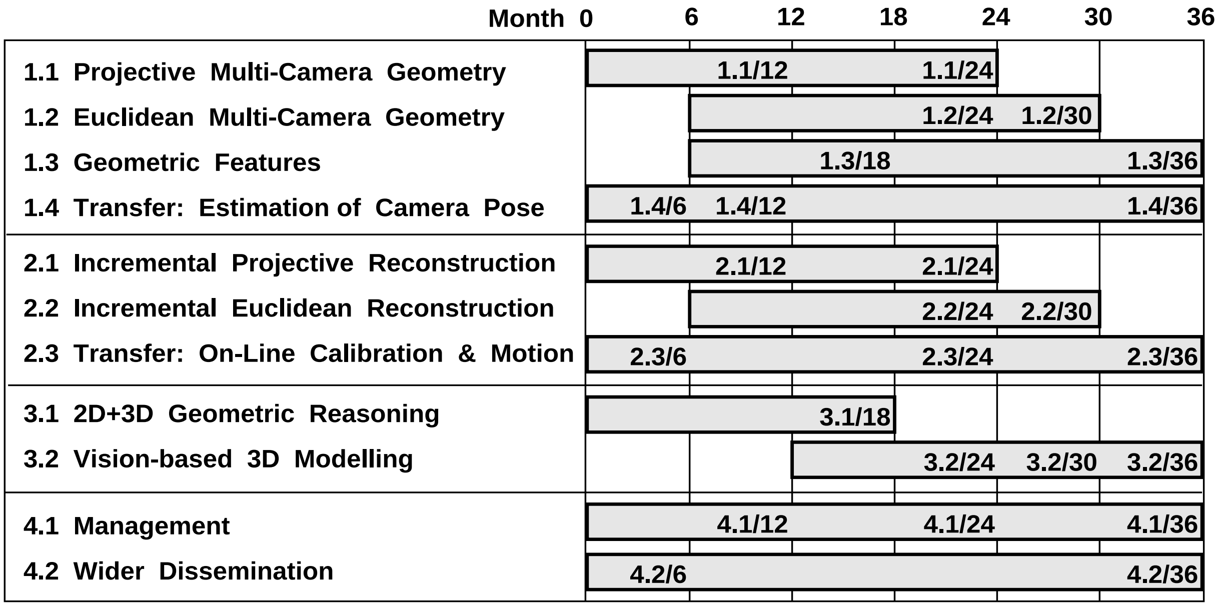

Figure 1: Tasks and their associated deliverables *vs.* time. For example 1.1/12 is the month 12 deliverable of task 1.1. The tasks and deliverables are described fully under each work package.

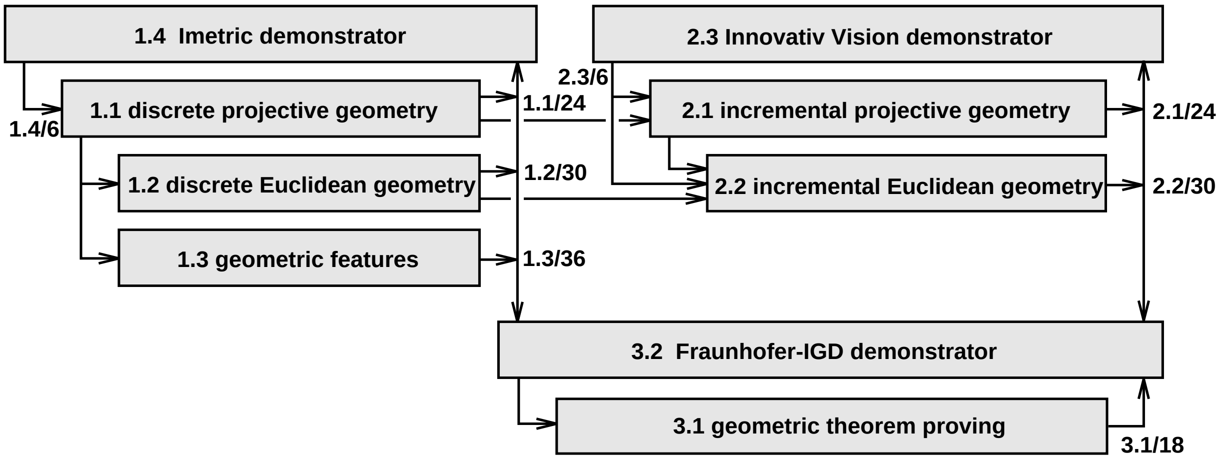

Figure 2: Graph of the main dependencies between the research and development work tasks. The most critical deliverables are also shown. The development tasks 1.4, 2.3 and 3.2 provide specifications and test data to the scientific tasks via deliverables 1.4/6 and 2.3/6, and use their end results via deliverables 1.1/24, 1.2/30, 1.3/36, 2.1/24, 2.2/30 and 3.1/18.

TASK	PERIOD	Gren.	Soph.	Lund	I.V.	Imetric	Fraun.	TOT.
1 Discrete Images	0–36	17	12	17	2	17		65
1.1 Multi-camera Geometry	0–24	4	5	4	1	1		15
1.2 Euclidean Structure	0–36	4	5	4		1		14
1.3 Features & Uncertainty	0–36	4		4	1	1		10
1.4 Transfer Imetric	0–36	5	2	5		14		26
2 Image Streams	0–36	15	11	14	20			60
2.1 Incremental Geometry	0–24	5	5	5	1			16
2.2 Continuous Constraints	6–30	5	5	5	1			16
2.3 Transfer I.V.	0–36	5	1	4	18			28
3 Reasoning	0–36	3	24	7			22	56
3.1 Geometric Reasoner	0–18	2	12	4			11	29
3.2 Visual Applications	12–36	1	12	3			11	27
4 Management & Dissemination	0–36	13	3	3	3	1	2	25
4.1 Management	0–36	12	2	2	2	0.5	1	19.5
4.2 Wider Dissemination	12–36	1	1	1	1	0.5	1	5.5
TOTAL	0–36	48	50	41	25	18	24	206

Table 1: Man months devoted to each work package and task at each site.

MONTH	DELIV.	CLASS	DESCRIPTION
6	1.4/6 (*i*)	P	Report: problem specifications & plan of action for WP 1 & 2
	(*ii*)	C	Data set: IMETRIC test object
	2.3/6 (*i*)	P	— continuous image part of 1.4/6(i)
	(*ii*)	C	Data set: INNOVATIV VISION test sequences
	4.2/6	P	WWW page installed
12	1.1/12 (*i*)	P	Short article: algebraic multi-image projective geometry
	(*ii*)	P	Algorithms: discrete multi-image projective reconstruction
	1.4/12	C	Data set: IMETRIC industrial object
	2.1/12 (*i*)	P	Short article: incremental multi-image projective reconstruction
	(*ii*)	P	Algorithms: incremental multi-image projective reconstruction
	4.1/12	P	Periodic Progress Report #1
18	1.3/18	P	Algorithms: camera pose from lines & conics
	3.1/18	P	Demonstration: prototype geometric reasoning software
24	1.1/24 (*i*)	P	Overview article: discrete & continuous multi-image projective reconstruction
	(*ii*)	P	Library: discrete multi-camera projective reconstruction
	1.2/24 (*i*)	P	Short article: algebraic multi-image Euclidean reconstruction
	(*ii*)	P	Algorithms: discrete multi-image Euclidean reconstruction
	2.1/24 (*i*)	P	— continuous image part of 1.1/24(i)
	(*ii*)	P	Library: incremental multi-image projective reconstruction
	2.2/24 (*i*)	P	Short article: continuous multi-image Euclidean reconstruction
	(*ii*)	P	Algorithms: continuous multi-image Euclidean reconstruction
	2.3/24	P	Library: robust feature tracking & motion segmentation
	3.2/24	P	Article: automated geometric reasoning for 3D properties
	4.1/24	P	Periodic Progress Report #2
30	1.2/30 (*i*)	P	Overview article: discrete & continuous multi-image Euclidean reconstruction
	(*ii*)	P	Library: discrete multi-image Euclidean reconstruction
	2.2/30 (*i*)	P	— continuous image part of 1.2/30(i)
	(*ii*)	P	Library: continuous multi-image Euclidean reconstruction
	3.2/30	P	Demonstration: FRAUNHOFER-IGD modelling system
36	1.3/36	P	Library: camera pose from discrete images & CAD models
	1.4/36	R	Demonstration: IMETRIC system
	2.3/36	C	Demonstration: INNOVATIV VISION system
	3.2/36	P	Article: automated geometric reasoning for data-base coherence & uncertainty
	4.1/36	P	CUMULI Final Report & technology implementation plan
	4.2/36	P	Section on industry workshops & wider dissemination in Final Report

Table 2: Deliverables by month. ‘Short’ and ‘long articles’ are submission-ready drafts suitable respectively for conferences and journals. ‘Algorithms’ are unpolished initial implementations, ‘libraries’ are stable research-level implementations with some documentation (suitable for use in technology demonstrators but not necessarily in industrial end products). The distribution classification is P=‘public’, R=‘restricted’, C=‘confidential’.