# UAV/UCAV NAVIGATION SYSTEMS - PRESENT AND POTENTIAL FUTURE

Richard K. Arning, Andreas Langmeier, Erwin Stenzel, Hermann Diehl, Gerald Sobotta
EADS Innovation Works
81663 München
Germany

## 1. INTRODUCTION

Navigation, the Latin word for the art to calculate position, orientation and route, is a fascinating science with its various aspects and impacts on history, technology, economy and social life. Originating from the seafarers, astronomers and architects in the antique, being developed further for aerospace applications, navigation has evolved from a secret knowledge, over a discipline for specialists to a daily tool finding its way into everybody's personal mobile life. The recent success of GPS, the Global Positioning System, has brought new potential and challenges of a high-tech but vulnerable infrastructure.

For unmanned or autonomous aerial systems the permanent availability of mature and precise information about position and attitude is a prerequisite for safe flight and successful mission completion. The man-made artificial technical solutions to provide data about the vehicle's position like radio-bearing, satellite navigation and inertial sensors have been successfully implemented in the last decades to unmanned flying systems but still face limitations: May it be, that inertial sensors with high-precision long-term stability are too bulky and too expensive for smaller aerial vehicles or that GPS signal reception suffers constraints by the natural environment, there are enough inherent hurdles to overcome. Also external impacts to GPS like sun storms or the usage of GPS jammers, which can be bought over the internet for less than one thousand dollars and having been used in the last gulf war, makes complementary navigation systems necessary.

It is remarkable to see, that the ancient technologies of the seafarers, terrestrial navigation with plummet, compass and visual bearing as well as astronavigation find their pendant in recent research programs on navigation solutions for unmanned systems. Visual navigation with landmarks, dead-reckoning by using the optical flow in down-looking camera picture streams or the usage of onboard-cameras observing the star's positions to determine the attitude of high flying vehicles have been made possible by a strong progress in sensor electronics and computing power.

Also it should be mentioned, that accuracy requirements to the navigation sensor suite can be far higher from the onboard mission system side than from the classical flight-guidance and -control side. Control of seeker-heads and camera turrets, labelling of mission sensor data, stabilisation of optical links and antennas, precise steering of laser weapons and target designators are just some examples for high precision demanding applications.

This paper aims at giving an overview about the state of the art in navigation system solutions for unmanned aerial vehicles as well as an outlook, on what can be expected for the future based on current research programs. Navigation herein is understood in the sense of localisation and attitude estimation, often referred also as "pose-estimation". Specific questions of relative positioning, e.g. for automatic landing or sense&avoid applications are not tackled in this article.

## 2. INERTIAL NAVIGATION AND GPS

### 2.1. Inertial Navigation

Today most modern Inertial Navigation Systems' (INS) are based on strap-down technology [1]. An INS integrates data gathered from an assembly of gyroscopes and accelerometers in order to determine the current state of the system (position, velocity, orientation) in an absolute reference frame. The inertial sensor package often is denoted as Inertial Measurement Unit (IMU), whereas the complete system, including digital processing unit and navigation software, is called INS.

The performance of an IMU/INS is determined by the quality of sensors and their alignment [2]. Because of inherent sensor errors (bias, scale factor, noise etc.) leading to unrecoverable drift effects, an INS is long-term unstable. Hence inertial sensors are often classified according to these errors into: low grade (rate grade), tactical grade, and navigation grade sensors [3].

| Error sources | rate grade | tactical grade | navigation grade |
|---|---|---|---|
| Bias stability [°/hr] | 10-1000 | 0.1-10 | <0.01 |
| Angle random walk [°/√hr] | >0.5 | 0.05-0.5 | <0.001 |
| Scale factor accuracy [ppm] | $10^3$-$10^4$ | 100-1000 | <100 |

TAB 1: Classification of gyroscopes

Gyroscopes frequently used in IMUs are Ring Laser Gyros (RLG), Fibre Optic Gyros (FOG), vibrating quartz gyroscopes, and more recently also silicon solid state sensors manufactured using Micro-Electro-Mechanical Systems (MEMS) technology. MEMS inertial sensors are attractive because they are low-cost, small, lightweight and low-power. MEMS rate grade accelerometers and gyroscopes are already widely used in automotive and consumer applications [3].

Especially MEMS gyroscopes often achieve only rate grade performance and hence can't be used in general for navigation purposes. Currently MEMS accelerometers have achieved a higher development stage than gyros and are already – e.g. the all-silicon SiAc™ - integrated in navigation grade systems as the LTN-101E GNADIRU - Global Positioning, Air Data, Inertial Reference System from Northrop-Grumman. Driven by specific applications as gun-hard guidance systems for munitions and tactical grade navigation of missiles and UAVs/UCAVs there are ongoing strong efforts to push MEMS gyroscopes to tactical grade level and beyond [4], [5], [6].

## 2.2. Global Positioning System

The satellite-based NAVSTAR Global Positioning System (GPS) radio navigation system of the United States Department of Defence originally was developed and operated to support military navigation [7]. Today it is used world wide in civil applications (airborne, car, logistics etc.) as well.

GPS currently is the only Global Navigation Satellite System (GNSS) system providing world wide coverage, availability and high-accuracy. Other GNSS under development are the European Galileo system, the Chinese BEIDOU/COMPASS system and the Russian GLObal NAvigation Satellite System (GLONASS) [8]. GLONASS development started early in 1976 [9], but fell in disrepair and is currently restored in cooperation with India.

GPS today is capable to provide positioning accuracies between millimetres and some meters, depending on receiver and augmentation technology. Differential GPS (DGPS), and Satellite Based Augmentations Systems (SBAS) [8] are used in all situations where satellite geometry is acceptable and uninterrupted signal reception is possible (FIG 1). In scenarios where GPS signals are completely lost or degraded unintentionally (e.g. in urban canyons, forests etc.) or intentionally by jamming, GPS either has to be replaced by another system providing continuous navigation or it has to be integrated with other sensors to bridge periods of no or bad signal reception.

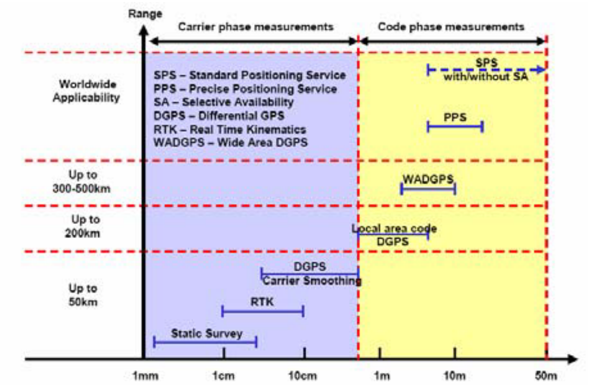


FIG 1. (D) GPS position accuracy (1σ horizontal)

The GPS spread-spectrum signal offers some inherent anti-jam protection but nevertheless the signals can easily be suppressed throughout a given area by a jamming device generating signals with enough power and suitable temporal/spectral signature. The reason for this is, that GPS satellites produce low-power signals that must travel great distances to reach the receiver, whereas a jamming device can produce a stronger signal much closer to the receiver. Hence the jammer has a distinct advantage. GPS receivers and chips required for very different applications, ranging from car navigation (low accuracy, small size) over military UAV/UCAV applications (high accuracy, anti-jamming and anti-spoofing capability) to surveillance applications (high accuracy, nearly arbitrary form factor), are available on the commercial and the military market from numerous suppliers (Thales, Trimble, NovAtel, Topcon, Javad, Rockwell Collins, BAE, Garmin, Sirf etc.).

## 2.3. GPS/INS Integration

INS is an ideal “sensor” for integration with long-term stable GPS information, which is an inherent weakness of each INS. Usually the INS is the primary “sensor” to estimate attitude and is also advantageous by its autonomous way of operation requiring no external infrastructure and its inherent anti-jamming capability. Synergistic effects in GPS/INS integrated systems are well reported in many studies [10], [11].

For all these reasons GPS/INS integration is widely used in different navigation applications to provide an overall system that has superior performance and overcomes the weaknesses of each sensor [12]. This development has been strongly boosted by the upcoming of MEMS inertial sensors in the last two decades. Currently several architectures working at different integration levels are used for GPS/INS integration [11], [13].

### 2.3.1. Loosely coupled INS/GPS

In loosely coupled GPS/INS systems position/velocity estimation by a filter residing in the GPS receiver is processed in a second navigation filter to aid the INS. This often is denoted as a decentralized or cascaded filter approach. For successful aiding it is essential, that at least four satellites are visible. Another problem of this approach is, that time-correlated errors of GPS position/velocity aiding measurements may lead to suboptimal performance or even instability of the navigation filter. It provides a not optimal solution because process noise has to be added to two filters and therefore the filtering capability of the system is reduced. Implementation of this architecture is advantageous if for example an existing stand-alone INS has to be integrated with a minimum amount of cost and complexity. As a consequence this approach provides only limited performance improvement.

### 2.3.2. Tightly coupled INS/GPS

In a tightly coupled GPS/INS raw GPS-data (pseudo-range, delta-range, Doppler measurements, carrier phase measurements) is processed directly in one centralized navigation filter [14]. A main advantage of tight-coupling against loose-coupling is, that in case there are less than four satellites, visible aiding of INS with the remaining raw GPS measurements is still possible. This scheme allows online calibration of inertial parameters and thus improves performance significantly in providing some immunity against GPS outages in terms of coasting time upon loss of signal. These features make the tightly coupled approach appealing for UAVs operating in mission scenarios where the choice of flight path or hostile jamming may cause reduced GPS availability.

### 2.3.3. Ultra-tightly coupled INS/GPS

In the final level of ultra-tightly or deeply coupled integration, GPS and INS are no longer distinct subsystems, but have to be considered as a single entity [15]. Inertial information is used to aid acquisition and signal tracking of the GPS receiver. Within this architecture the IMU and the navigation filter are combined with the tracking loops of the receiver into a single filter. This approach requires access to receiver firmware or at least tracking loop information. It offers improved robustness and accuracy to the overall system and allows faster signal acquisition and re-acquisition and thus optimises the availability of GPS information. As long as the jamming signal power does not exceed the anti-jamming threshold of the system, the jamming signal is rejected and navigation, using both GPS signals and inertial measurements, continues. As a consequence deep coupling significantly improves the anti-jamming capability and hence provides best advantage in enhancing survivability in the presence of GPS interference.

Kalman filtering [16], [17] can be considered as the standard state estimation approach used within GPS/INS integration but in the last years also other techniques have been considered for fusion of GPS with INS [18], [19].

## 2.4. INS/GPS systems for UAVs/UCAVs

In the following hybrid GPS/INS navigation systems used on different UAV/UCAV platforms will be introduced to illustrate the variety of systems already in use. One focus will be on GPS/INS systems that are based on tactical grade INS (IMUs). These systems benefit strongest from the new developments in the field of enabling MEMS and are appealing for navigation of UAV platforms because they cost less than traditional systems and in addition they are smaller, lighter and low power consuming.

Finally some words will be said about navigation systems (GPS/INS systems, autopilots etc.), that are based on low-cost rate grade MEMS inertial sensors.

There is no claim on completeness here and it has to be mentioned that for many new developments, as for example the recently presented Barracuda UCAV from EADS Military Air Systems or Dassault's Neuron, the most relevant information concerning navigation is confidential and therefore can't be presented here.

### 2.4.1. Low-cost Quartz INS/GPS

The Outrider™ "Tactical Unmanned Aerial Vehicle" (TUAV) used the "Digital Quartz Inertial Measurement Unit - Navigation Processor™" (DQI-NP) [20] coupled with a custom Trimble GPS receiver as a low cost off-the-shelf GPS/INS solution. The RQ-6 Outrider from Alliant Techsystems has a MTOW (maximum take-off-weight) of about 185 kg. The DQI-NP originally developed by Boeing is part of the C-MIGITS family of products. An overview about the Outrider™ navigation approach can be found in the literature [21].

The current products from Systron Donner based on this technology are the tactical grade C-MIGITS™ III (DQI coupled with Jupiter® LP GPS receiver) and the even smaller Miniature MEMS Quartz GPS/INS System MMQ-G with MMQ50 IMU and Jupiter®PICO GPS receiver.

The C-MIGITS™ III has been chosen as the primary navigation system for the SHARC© (Scouting and Hunting Autonomous Rotor Craft) Helicopter-UAV flying testbed currently under development at EADS Innovation Works (IW), the EADS research organization [22]. SHARC© features an MTOW of 200kg including a payload capacity of around 50kg.

### 2.4.2. Tactical grade and high end INS/GPS

The RQ-4 Global Hawk UAV, the world's largest UAV in operational service with a weight of about twelve tons, was developed by the Northrop Grumman's Ryan Aeronautical Centre to perform high altitude image based reconnaissance. In a joint-venture with EADS a SIGINT (SIGnal INTelligence) version called *EuroHawk* is designed for the German Luftwaffe. The navigation system of the Global Hawk utilizes special category 1 (SCAT-1) differential (DGPS) system to provide sufficient navigation accuracy for taxi, takeoff and landing operations [23]. In addition the commercial world wide available DGPS service, OmniSTAR, was investigated with regard to landing capabilities in the event of an emergency landing at sites not instrumented with a SCAT-1 ground system.

*FOG IMU & DGPS*

The primary navigation system originally chosen was the LN-211G (D)GPS/INS system from Northrop-Grumman. The LN-211G consists of a LN-200 FOG IMU and a Magnavox MX-7212 GPS receiver ready for accepting differential corrections.

*RLG IMU & DGPS with RAIM*

Recently this navigation approach has been replaced by two redundant Kearfott's KN-4072 systems. The KN-4072 is an example of a GPS/INS system featuring RLG technology – Kearfott's Monolithic Ring Laser Gyro (MLRG). This system weights less than 5 kg and utilizes a single frequency (L1) DGPS ready GPS receiver with Receiver Autonomous Integrity Monitoring (RAIM) capability.

*RLG IMU & dual band GPS with SAASM*

Another system from Kearfott, the KN-4073b, has been chosen by the United States Navy and Army for the Fire Scout Vertical Tactical Unmanned Aerial Vehicle (VTUAV). The RQ/MQ-8 Fire Scout is based on the manned helicopter Model 333 from Schweizer Aircraft Corporation. The KN-4073b again is based on MLRG technology and features a dual L1/L2 operating frequencies, differential ready Selective Availability / Anti-Spoofing Module (SAASM) P(Y)/C/A code, WAGE (Wide Area GPS Enhancement) capable GPS receiver.

*Other high end INS/GPS systems*

Important suppliers of navigation grade IMUs and high-precision GPS/INS systems besides Honeywell are Northrop-Grumman and Thales Navigation. These systems, often used on manned military aircrafts and in civil aviation, are rather expensive and bulky and hence are affordable only on larger UAV/UCAV platforms.

### 2.4.3. MEMS INS/GPS

*Ultra-tightly MEMS INS/dual frequency GPS with SAASM*

Integrated Guidance Systems (IGS) LLC, a Honeywell International/Rockwell Collins joint venture, recently has introduced the IGS-200, a deeply integrated guidance system ideally suited (g-hardened) for artillery and missiles but also applicable for UAV missions. Because of ultra-tightly GPS/INS coupling and use of a SAASM dual-frequency GPS receiver the system provides increased accuracy in GPS jammed or denied environments.

This system is based on Honeywell's MEMS technology development [24], [25], which has led to the currently available MEMS IMUs HG1900 and HG1930. These IMUs are designed for projectiles, missiles, smart munitions and unmanned vehicles (Ground and Aerial Vehicles).

The SINAV02™ from BAE Systems has been developed for the same purposes and it is providing similar functionality as the IGS-200. It is based on BAE Systems' miniature, MEMS IMU (SiIMU02) and state-of-the-art military GPS receiver technology.

### 2.4.4. Multi-sensor integrated systems

*Magnetometer*

General Atomics Aeronautical Systems' has chosen Athena's GuideStar™ GS-511 integrated (D)GPS/INS and air data system to provide dual back-up navigation capabilities to their Warrior™ which is derived from the combat-proven Predator® unmanned aircraft system. The GS-511 used on Warrior features a tactical grade HG 1700 IMU from Honeywell International, a Trimble Force-22 differential ready GPS with SAASM option and built-in tri-axial magnetometer.

*Magnetometer and barometer*

Another system from the GuideStar™ series, the GS-311, has been chosen to provide control and navigation capability to the Sky-X UCAV from Italy's Alenia Aeronautica. This system features solid-state MEMS gyros and accelerometers. In utilizing information from inertial sensors, integrated GPS, a barometric altimeter and a tri-axial magnetometer, Kalman filtering algorithms provide a tactical grade strap-down navigation solution.

Athena's approach to guidance and navigation, which is based on the additional use of aiding sensors (tri-axial magnetometers, air data sensors etc.), shows that within a proper sensor fusion even with MEMS sensors a navigation and control system solution appropriate for tactical UAVs can be achieved.

*Attitude by GPS*

The more classical Honeywell IMU HG1700 is based on tactical grade RLG technology. The HG1700 IMU for example is part of the avionics package of the small – gross take-off weight is about 20 kg - fixed-wing DragonFly UAV experimental test bed developed at the Stanford University [26]. The avionics of the DragonFly include a customized 40 channel, five-antenna GPS board developed in the Advanced Technology Group at Trimble Navigation Limited providing GPS attitude.

Another small fixed-wing UAV utilizing a multiple antenna system with two BAE Systems Allstar™ GPS cards for avoiding GPS loss under special flight manoeuvres, is the MK3-Brumby developed at the University of Sydney [27]. The IMU of the MK3-Brumby is the short-range tactical grade 250 g ISIS unit from Inertial Science, Inc. The MK3-Brumby navigation system in addition includes a barometer for additional aiding within a complementary INS/GPS/Baro Kalman filter.

### 2.4.5. Rate grade sensors based autopilots

In the second half of the nineties a real boom of mini- and micro UAV-projects started in the US boosting the development of miniaturised autopilot systems with integrated FCS-concepts (Flight Control Systems), in which the FCC (Flight Control Computer) was no longer separated from the sensors. This development was triggered by new military scenarios requiring "over-the-hill"- or even "indoor"-reconnaissance means and by a technology push in electronics, making miniaturised sensors and powerful microprocessors available.

An exhaustive list of such system providers, most of them small enterprises having originated in the last years e.g. from university spin-offs and MoD-funded or other governmental-funded research projects, would be too long, so that only the fundamentals and some examples are given. Also a lot of these small systems are based on the same sensor-components, where still only a few manufacturers exist, so that the performance figures are comparable.

In Europe former Dornier GmbH (now EADS Military Air Systems) in cooperation with the Technical University of Aachen was among the first by starting development already in 1998. The developed system is shown in FIG 2.

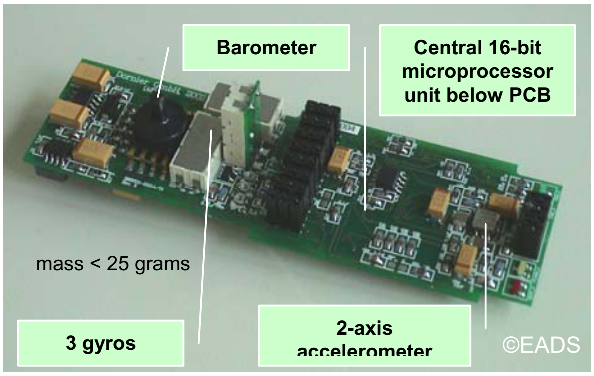


FIG 2. EADS Integrated Autopilot for Micro Aerial Vehicle

The design and the performance figures of the sensors used are described in [28]. Meanwhile a lot of commercially available systems are on the market and even the toy-industry is offering MEMS based autopilots for radio-controlled planes and helicopters.

Other representative test results have been published for instance in [29]. The Crista IMU from Cloud Cap Technology Inc. is built from Analog Devices MEMS accelerometers and gyroscopes. It's a typical rate grade IMU with a bias of about 500 °/hr. It is outlined that hybrid navigation is possible with the Crista IMU, but only if GPS is almost always available or information from other aiding sensors (altimeter, compass, air speed, etc.) can be utilized. It is stated, that performance is much worse than with a GPS/INS integration based on tactical grade IMUs.

These findings are typical for GPS/INS integrations based on low grade MEMS inertial sensors. If the performance of the inertial sensors is too low, integrated navigation systems have little potential to bridge even small GPS outage periods with an acceptable loss of positioning accuracy. Even the estimated attitude values are drifting so fast in case of GPS-aiding-loss, that without taking further measures wrong bank- and pitch-angles would cause a crash of the aircraft. To avoid this, often simple flight-mechanical models and barometric sensing are used to deliver aiding information for the INS.

One measure to overcome the shortcomings by too erroneous gyroscopes is the integration of an additional tri-axis magnetometer providing information about orientation. This type of integration is widely used especially in systems which are based on low grade MEMS gyroscopes. It provides improved accuracy at comparable low cost. Examples of GPS/INS based systems utilizing this type of aiding are for instance the GuideStarTM series (GS-311, GS-511) from Athena, the FAA certified NAV420 AHRS from Crossbow, and the MIDGII from Micropilot.

## 2.5. Current developments and future trends

For the safe use of stand-alone GPS and GPS/INS based navigation approaches in all types of UAVs/UCAVs, military as well as civil, effective measures to reduce the vulnerability of satellite-based navigation (current GPS, future GNSS) are a major concern.

Already since 2006 SAASM is used by all newly deployed military GPS receivers. SAASM functionality allows direct acquisition (from satellite) and decryption of precise GPS Y-code. This leads to an increased anti-jamming capability typically in the range of 10 to 20 dB better than the former Precise Positioning Service–Security Module (PPS-SM). Other anti-jamming measures are already available or under development. To mention here are adaptive GPS antennas (e.g. controlled reception pattern antennas – CRPA), the use of multiple antennas [30], and also the implementation of more advanced algorithmic approaches [31] than traditional RAIM methods [32], [33], frequently used for integrity monitoring purposes.

The already started evolution of more precise MEMS based gyroscopes with the final goal of navigation grade sensors (see e.g. DARPA program NGIMG - Navigation-Grade Integrated Micro Gyroscopes), will allow the development of more precise, smaller, and lower cost GPS/INS systems in the future. Micro Opto Electro Mechanical (MOEM) inertial sensors, which make use of guided wave optical phenomena controlled by micromechanical structures, seem to have potential for high performance future INS [34].

For UAV/UCAV applications affording high anti-jamming resistance ultra-tightly coupled GPS/INS architectures most probably will become a standard. Other applicable anti-jamming measures may in addition be implemented to further minimize vulnerability to GPS interference. What currently can be achieved in proceeding this way is illustrated by the high-G, MEMS based, deeply integrated guidance, navigation and control Flight Management (FMU) from IGS LLC, a 14 cubic inch package, achieving tactical grade performance, and 89 dB of jamming suppression [35].

Another development which will positively affect the use of stand-alone GPS and hybrid GPS/INS UAV/UCAV navigation is the modernization of GPS [36]. The new civilian L2C signal will lead to improved accuracy and also can act as a redundant signal in case of localized interference. Of even more importance for military users will be the new military signal (M-code), which was designed to further improve anti-jamming methods and secure access to signals. The M-code is intended to be broadcasted from standard wide angle (full Earth) and in addition as a spot beam from a high-gain directional antenna which will increase the signal strength locally in a specific area of several hundred kilometres in diameter by about 20 dB.

The development of the European Galileo system and the restoration of GLONASS finally will lead to a combined inter-operable GNSS with nearly 80 satellites in world wide operation. This fact in conjunction with the extended and optimized signal structures of the overall system will provide higher accuracy, availability, continuity and integrity to military and civil users of this system 0, [37], [38].

Receivers capable to track all-in-view GPS and Galileo satellites are already available at the Belgian company Septentrio [39]. The Canadian company NovAtel's 15a receiver offers 16-channel tracking of GPS L1/L5, Galileo L1/E5a and SBAS signals. Topcon, a company active in the field of high-end GNSS already has developed receiver technology (G3) which combines all three satellite-based positioning systems and is capable to universally track 72 channels. For the future it is very reasonable that different types of more advanced multi-sensor fusion approaches, based on INS, GNSS and other subsystems, will become more standard for the operation of UAVs/UCAVs in different flight phases.

# 3. RADIO NAVIGATION SYSTEMS

A merely radio navigation based approach to hybrid navigation is GPS/LORAN integration [40]. The already existing Loran (LOng RAnge Navigation) is considered to be a backup candidate to GPS with absolute accuracies between 0.1NM to 0.25NM and has been investigated by the U.S. Coast Guard (USCG) and Federal Aviation Association (FAA) to be improved (enhanced Loran - eLORAN) [41] towards accuracies of 30 metres.

Already in the last decade of the 20$^{th}$ century the so-called Integrity Beacon Landing System (IBLS) has been developed [42], where the Integrity Beacons are low-power, ground-based pseudolites (PL) that transmit GPS-like signals. With these beacons centimetre-level accuracy and high integrity can be achieved during landing, flare and rollout as demonstrated successfully, for example at automatic landings of the X-31 [43], the Boeing 737 [44], and the Outrider™-TUAV [45]. IBLS technology originally has been marketed by the company IntegriNautics which doesn't exist anymore. Its successor Novariant Inc. provides precision solutions for aerospace applications. Applications include the Boeing 737 Landing System and the X-31 Landing System. Precision solutions are based on Real-Time-Kinematic (RTK) positioning and deployable infrastructures (pseudolites) to augment GPS coverage in areas with problematic GPS signal reception conditions.

With EADS Astrium also a European supplier of pseudolite technology is on the market. The NSG 5100 GNSS Signal Generator is a flexible and modular signal generation unit for laboratory & field testing of GNSS equipment as well as for providing GNSS Pseudolite signals in various environments. Integration of GPS/INS with pseudolites at different coupling levels is still a research issue [46], [47], [48].

The KZO (Kleinfluggerät ZielOrtung) from the German company RDE features a specific solution by localising the UAV through elevation and azimuth of the data-link, manufactured by EADS Defence Electronics. This approach ensures GPS-independence but is of course limited to LOS- (Line-Of-Sight) conditions.

CL-289, a fast tactical UAV system in-service in the German and French army, was designed to rely for its primary navigation system on a totally GPS-independent approach using a Doppler Radar with four-beam Janus configuration. Accuracies of the 3D-velocity measurement over terrain of such radars are reported to achieve better values than 1% in each axis. In addition the altitude over ground is calculated by the onboard computer. Operational constraints are maximum range of the Doppler Radar (limits altitude), sharp steps in terrain altitude, very dynamic manoeuvres, weather conditions, and specific characteristics of the surface (e.g. due to snow, open water at very smooth sea states...). Anyhow, the drift of the dead-reckoning navigation system of the CL-289, consisting of the Doppler Radar and two high precision 2-axes mechanical gyros, is very low, indicated by the fact, that the UAV could be captured by a landing beacon even after 400 km of flight. High precision alignment of the UAV in azimuth is necessary in the launch phase due to dead-reckoning navigation approach. Originally developed by Bombardier and Dornier, the system was upgraded by EADS [49] with a dual-band GPS-receiver from Thales but CL-289 can still be operated in conditions off GPS-loss or under jamming conditions.

## 4. IMAGE BASED NAVIGATION

Using a picture or a series of pictures (video-stream) taken from the UAV, these pictures may be used in image based navigation (IBN) to:

- Determine the geo-referenced position of the UAV(-camera) by comparison with maps and aerial images stored in on-board or on-ground data bases
- Estimate the relative position and attitude of a (3D-) object towards the UAV (e.g. the UAV's position relative to a known landmark or a targets position relative to the known UAV-position)
- Have an INS back-up or alternative solution for attitude calculation
- Measure the relative motion over ground to calculate changes in position, comparable to the Doppler Radar function described in the previous chapter
- Navigate between obstacles

It should be mentioned, that although computer vision has many characteristics that make it suitable for such navigation tasks on a UAV, it does present many challenges too. Vision outdoors is notoriously difficult because of varying lighting conditions. Even if the lighting is favourable and the scene can be captured accurately in an image, there is the problem of making sense of the image and extracting information. Also image comparison with data-bases features inherent challenges not only by differences of lighting conditions between the actual image and the image data base but also due to changes of the environment itself over time (new objects, destruction, snow...).

Although the development of machine vision as a secondary or primary means of aircraft navigation has seen a fair amount of progress over the last years in numerous research programs, the implementation in products and airworthiness-certification of these technologies however remains seldom done. Nevertheless recent advances in the field of machine vision have shown great potential for vision sensors as an alternative to GPS in inertial navigation for obtaining aircraft position data. The motivation to deal with these techniques is mainly due to the desire to navigate under conditions, where GPS or terrain data are not available with the necessary precision or frequency and the drift of an inertial strap-down solution is too large for sustained autonomous flight in environments as urban areas and at low altitudes where a GPS receiver antenna is prone to losing line-of-sight with satellites. Problems might also be encountered for vehicles operating in hostile environments where reception of GPS signals might possibly be jammed or otherwise denied. With a wealth of information available in each captured image frame, camera-based subsystems have a large margin for growth as onboard sensors. Furthermore vision sensors allow for feature-based navigation through surrounding environments – a task impossible with GPS and inertial sensors alone [50]. Image sequences alone can not provide absolute velocity data, if size and geometry of objects are not known. There must be at least one range measurement device to complete this task. Typical onboard sensor systems, such as radar and infrared range finder, can provide measurements of this kind.

Compared with other navigation systems, a vision-based navigation system has higher computational and structural cost. Janschek, Tchernykh and Dyblenko [51] use, in order to cope with real-time requirements, a compact embedded "Optical Joint Transform Correlator", which allows using image motion tracking in mobile applications, such as airborne and space borne remote sensing systems.

An IBN system used for relative navigation deals with the determination of a subset of flight state parameters from EO, IR or SAR image sequences that can be utilized to support the UAV's INS. The objective is the replacing of linear acceleration and angular velocity signals from an INS with linear velocity and angular velocity signals from an IBN system. The measurement of self-motion from images is a well studied problem in robotics and computer vision [52]. Nearly all techniques are inherently based on a single camera/imaging device model. The techniques employed differ primarily on whether features in the image are identified or not. Methods based on the former rather than the latter tend to need more computational power.

Basically, there are two types of methods to derive translational and rotational parameters of ego-motion from image sequences. Firstly the classical, dense field, optical flow calculation and secondly the tracking of a set of features in consecutive image frames is used to calculate either a sparse OF field or to use the epi-polar constraint scheme to derive ego-motion via the analysis of the essential matrix. Each of these cues has its advantages and its own domain of application.

### 4.1. Optical Flow

Optical flow is a useful tool for many tasks in computer vision [53], [54]. Besides the use for the calculation of ego-motion, it has been applied to problems of motion-segmentation, time-to-contact and three-dimensional reconstruction (structure from motion) among others. Barron et al. [53] classify optical flow algorithms by their signal-extraction stage. This provides four groups: differential techniques, energy-based methods, phase-based techniques and region-based matching. Traditionally, most researchers in this field have focussed their efforts on extending the 25-year-old Horn and Shunck [55] or Lucas and Kanade's [56] methods, both of these are differential techniques and both are working with greyscale intensity images, EO or IR. It should be mentioned, that in the case of EO images there exists the possibility to work with other attributes of the optical signal, namely the colour or polarisation information [57]. Optical Flow is able to deliver angular rates and relative velocity vectors. With an additional range measurement one gets absolute velocities. Optical flow offers also the possibility to calculate the time-to-contact, if heading towards an object (plane) or equivalent, time-to-contact maps of the observed scene [58], [59].

### 4.2. Feature Tracking

Reliably tracking key points and textured patches from frame to frame is the basic requirement for a feature tracking method. Widely accepted is the Shi-Tomasi [60] feature selection criterion, that is ideally combined with the Lukas-Kanade algorithm shown in the picture below.

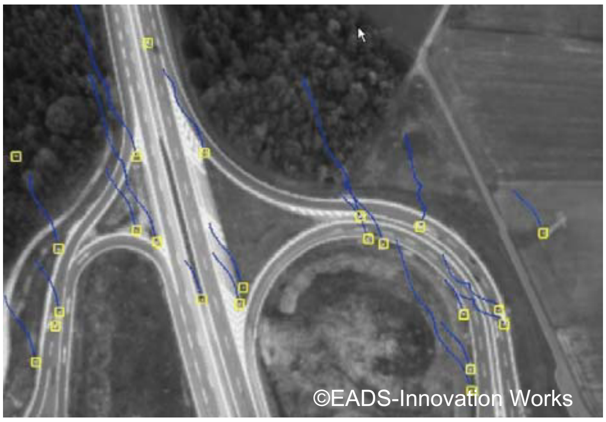


FIG 3. Combination of automatic feature selection and Optical Flow computation

Extending the feature selection to multiple scales, e.g. by utilizing Gaussian image pyramids, the features become scale-invariant, the tracking gets more robust and the drift minimizes [61]. Given a set of feature points that have been tracked over consecutive image frames, there are several approaches for deriving the motion parameters. The majority of these methods employ some form of the epi-polar constraint. The epi-polar constraint is a geometrical relationship that states, that the position vectors of a feature point relative to the camera at two instants in time are coplanar with the camera translation vector. An important implication of the epi-polar constraint is that the determination of the camera motion and the reconstruction of the three-dimensional scene can be decoupled. With at least five tracked feature points across two frames, the recovery of the camera motion can be reduced to the solution of a linear homogeneous equation. For the case where the camera is calibrated, the solution of this equation yields an approximation of the elements of the so-called essential matrix, from which it is straightforward to extract the rotation and direction of translation of the camera. The main problem here is the geometrical nature of such a constraint, that is poorly conditioned for high noise to signal ratios.

The problem of several moving objects in the image frames and the robust recovery of ego motion is addressed by Irani et al. [59]. A similar approach is the tracking of edges or general landmarks [62].
As outlined before, the feature tracking problem is traditionally addressed by establishing point correspondences and then applying classic geometry techniques. However, depending on the application, perhaps only partial scene reconstruction is necessary. In such cases computing the first-order differential invariants of image motion, namely divergence, curl and deformation, can directly provide information about scene structure, while avoiding complex projective geometry. Fu and Kowesi [63] propose a way to extract the differential invariants of image motion from an optical flow field using a bank of filters. The output of these filters can be used for the recovery of surface normals and time-to-contact calculation. T. Camus et al. [64] demonstrated, that by using only optical flow field divergence obstacle avoidance is feasible.

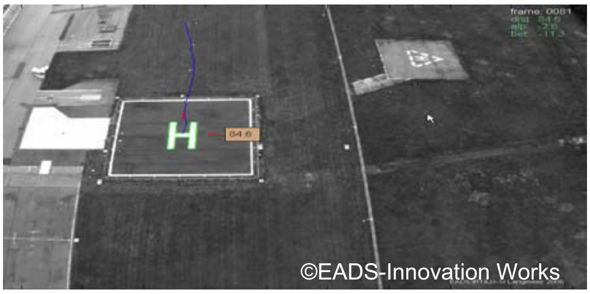


FIG 4. Cooperative marker recognition and tracking

## 4.3. Structure from motion

One possibility to recover a quasi 3-dimensional map of the scene is the use of the time to contact scheme from OF. Without additional measurement information one can calculate “time to contact maps” of the environment. The “structure from motion” concept utilizes features in the observed image sequence. Features for example can be tracked over a video sequence and when the baseline is large enough, the first and last images of the sequence can be used as quasi-stereo pair and the tracked features are matched for stereo reconstruction. This allows 3-D construction of the scene and comparison with preloaded terrain maps (chapter 5 on “Terrain Reference Navigation”).

## 4.4. Geo-Referencing

In order to get absolute geo-referencing, well defined landmarks have to be recognised by the IBN system. Landmarks for image based navigation which comprise surface structures and surface features (waypoints) can be derived from EO and IR images with 3D reconstruction and SIFT based scale invariant features (points, edges, ridges) [61], [62]. The absolute geo-referencing requires mission planning and real time recognition of the selected features.

The Tri-Tec navigation system for KEPT Taurus missile comprises some of these IBN methods. The terrain profile is constantly monitored with a radar altimeter and additionally, during a typical mission, approximately 10-20 waypoints (e.g. crossroads) are recognised by their simplified IR features and track update/correction may be performed. During the homing phase, the IR tracker performs target recognition and enables precise strike.

Similarly, the navigation system of the Storm Shadow UAV uses an IR camera for target recognition during approach. Likely, simplified IR signatures of the target are recognised and tracked.

## 4.5. UAV-Implementations of IBN

There are a growing number of applications of IBN in UAV systems using vision for both state estimation and control. Many research papers deal with helicopter-UAVs for which IBN is ideally suited, because they are flying relatively slow and at low altitudes making frame to frame feature tracking and feature selection comparatively easy. Automatic landing, even on ships, is reported in several papers [65], [66], [67], but not discussed here any further. IBN is also employed in fixed wing, military UAVs. But, notoriously, reliable and significant information about military systems is published less. In the following section we selected reports about IBN to show to what extent these methods are applied and what applications seem feasible.

Targeting directly an industrial application, Rathinam, Zu Whan Kim and Sengupta, [68] describe a control and image processing system to enable a UAV to track structures like oil-gas pipelines, roads and bridges. They stress, that UAVs could be a cheap way of executing these inspection functions, potentially revolutionizing the economics of this industry. Their paper describes an important component of such autonomy. A UAV carrying out inspection activities should be able to localize itself relative to the structure it is inspecting and control itself to stay on top of the structure. Their work is based on the assumption, that if the UAV stays on top of the structure with the requested precision, it should be possible to control the imaging or inspecting sensor to produce images with the desired coverage and precision.

In Bosse [69], optical flow-based motion estimates are combined in an extended Kalman filter along with IMU, GPS, and sonar altimeter measurements to provide a navigation solution for an autonomous helicopter. They report, that the use of optical flow is however restricted since it is reliable only in domains where the motion between images is expected to be small.

Koch und Thielecke [70], [71] from DLR also report on academic research on image based navigation without GPS and the support of IMU drift in the frame of the ARTIS (VTOL) project. They work with the tracking of ground features and Lukas-Kanade OF calculation. Additionally to the standard GPS, IMU and camera equipment they utilize a magnetometer and sonar for altitude measurements.

Amidi, Kanade & Fujita, [52] developed a system, termed visual odometer, that is capable to estimate helicopter position and velocity. It works by locking on to ground objects seen by a pair of on-board cameras (stereo system). Based on image template matching, the helicopter motion is estimated by sensing object displacement. Attitude information is provided by a set of gyroscopes while position and velocity are estimated based upon template matching from sequences of stereo vision data. In this approach, attitude estimates are not derived from the vision algorithm and it is assumed that the field of view changes slowly while the helicopter hovers above the same area.

Kim and Sukkarieh [72] report on augmenting a GPS/INS navigation system with a Simultaneous Localisation and Mapping (SLAM). The SLAM algorithm is a landmark based terrain aided navigation system that has the capability for online map building and simultaneously utilising the generated map to limit the errors in the Inertial Navigation System. SLAM is augmented to a GPS/INS system, which can provide information about the states of a vehicle without the need for a priori infrastructure such as GPS, ground beacons or a preloaded map. If GPS information is available, the SLAM integrated system builds a landmark-based map using a GPS/INS solution. If GPS is not available, the previously and/or newly generated map is used to constrain the INS errors. They show that their system can provide reliable and accurate navigation/landmark-map solutions even in a GPS denied and/or unknown environments.

The same authors, Kim et al. [73], present the real-time results of an air-to-ground feature tracking algorithm using a passive vision camera and a low-cost GPS/INS navigation system on a UAV platform. The vision payload is able to observe a number of ground features and the GPS/INS navigation system is used in conjunction with a waypoints-based guidance and flight control module. Due to limited processing resources the vision node employs a simple but fast algorithm based on a method of point feature extraction. The feature tracking performance is greatly affected by the accuracy of the onboard navigation system. Conversely though, it can be used as a performance indicator of the navigation filter by comparing it with the truth feature location and some simple geometry.

The University of Florida has developed a horizon tracking method that uses a statistical approach to determine the separation between the sky and the ground [74]. This has been validated as part of an autopilot for a micro UAV.

Providing accurate path-following (or trajectory-tracking, which includes timing) is a key challenge in obtaining full autonomy for UAVs. Rysdyk [75] describes a path following algorithm and demonstrates autonomous observation of a target from a UAV with a gimballed nose-mounted camera. It is shown, that camera angles can be maintained nearly constantly.

Nordberg et al. [76] present an overview of the basic and applied research carried out by the Computer Vision Laboratory, Linköping University, in the WITAS UAV Project. This work includes customizing and redesigning vision methods to fit the particular needs and restrictions imposed by the UAV platform, e.g., for low-level vision, motion estimation, navigation, and tracking. It also includes a new learning structure for association of perception-action activations, and a runtime system for implementation and execution of vision algorithms.

Schweyer, MBDA [62], presents landmark and OF based methods for navigation of a guided missile. He reports on the feasibility to calculate OF even over water surfaces.

The use of image aided navigation for UAVs' guidance and target geo-location in urban and GPS denied environments is discussed by Brown [77]. He states that a low cost, low grade MEMS IMU can be used as a UAV inertial navigation system. Doing so, calibration of the MEMS inertial instruments is essential. Applying GPS/Inertial metadata to imagery allows real-time targeting and mosaic generation and allows, what they call video updates (VUPT), to be applied to UAV navigation using known reference points. Therefore inertial VUPT aiding allows robust navigation with low grade MEMS IMUs following GPS drop-outs.

The technology of the well-known optical computer mouse, a simple 2D-calculation of the optical flow, was originally invented by Hewlett Packard for navigation of aircrafts! Meanwhile the first toy-autopilot for radio-controlled model helicopters developed by the German company Heli-Command is commercially available. The small device contains, besides three gyros, a down-looking camera used to control the position in hovering or the speed in forward flight via optical flow. Depending on the version the range is limited to roundabout 3 or 12 meters. The device was also integrated in micro UAV helicopters solving the problem of IMU-drift-compensation for attitude calculation when GPS is not available (e.g. indoor mission).

## 5. STAR SENSORS

### 5.1. Basics

Star sensors are widely used in space-borne applications and as such, they represent a successful implementation of a very specific method for object tracking. Because of their speciality and their niche application in UAV-systems, this paper treats them separately. Their advantages are high precision in attitude determination and zero drift. Normally they are not used to determine the position. Star sensors can be used for airborne and even terrestrial applications [78], [79], if there are no clouds occluding the stars. The high flying SR71 "Blackbird" supersonic reconnaissance jet was also equipped with a star sensor and some currently running UAV/UCAV programs integrate star seekers also in the navigation system architecture.

The functional principle of a star sensor is simple. Star positions are known very precisely. So a camera is used, which looks into the sky and takes an image of several stars. The images of the stars in the focal plane must be located with good precision. From the angular distance each pair of stars can be identified and via a star cata-logue the attitude of the camera can be calculated.

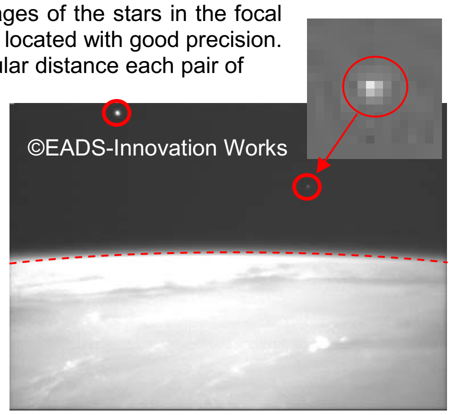


FIG 5.
Simultaneous earth limb and star localisation

A new concept of a combined star-earth tracker to give also information about orientation and distance to the earth centre was invented by EADS Innovation Works and EADS Astrium (see Fig 5).

### 5.2. Accuracies of Star Sensors

Most star sensors are much more precise than needed for standard airborne applications. Typical accuracies are in the range of arcsec, e.g. 1 arcsec for pitch and yaw and 6 arcsecs for roll angle of the camera coordinates in the SED 36 star tracker of EADS Sodern [80]. Even very cheap systems, built with commercial components, can achieve accuracies better than 0.01 [81], [82], which is far better than the camera resolution (number of pixels) itself. Typically the exploitation algorithms achieve sub-pixel accuracy of 1/10 to 1/100.

Daylight decreases the precision of star location, but this is not an essential problem. The background illumination by the scattered sun light is spread over many pixels by magnification, while the stars are point sources and thus focussed on a few pixels. For typical star sensor apertures of 30 to 50 mm [80], [83] stars of magnitude 3 to 4 should be observable even at sea level. For a high altitude vehicle the background is decreased by 6 dB. Fast rotations of the flying platform occurring during manoeuvres or gusts further limit the accuracy of the sensor information and should not exceed a few degrees per second.

## 6. TERRAIN REFERENCE NAVIGATION

The application of Terrain Reference Navigation (TRN) is state of the art in many products on the market. Prominent technologies are TERCOM and TERPROM. TERPROM® and TERPROM® II are trade marks of BAE Systems. We will shortly discuss some aspects of the underpinning technology, based on RADAR altimetry or IR imaging. In a recent dissertation [84] from 2006, entitled "Application of Airborne Laser Scanner- Aerial Navigation", a detailed overview is given. We will stress some aspects of future improvement of the state of the art, concerning the use of LASER altimetry and LASER 3D-imaging, based on former EADS inventions and data compression technologies.

### 6.1. TERCOM

The idea of TERCOM is based on the matching of terrain contours. These can be measured from an aircraft flying approximately with constant absolute altitude by a down-looking RADAR sensor. It has been patented in 1972 [85] by W. C. Hallmark, when the digital age allowed for the first time the storage of digital altitude maps.

### 6.2. TERPROM

Created in the same decade as TERCOM, the trade mark TERPROM® is now used for a more complex system, including the use of stored digital terrain elevation data and inputs from the aircraft's navigation system and Radar Altimeter to produce a highly accurate Terrain Referenced Navigation solution, as BAE System specifies. The integration of INS and GPS through a common Kalman Filter achieves improved results for TERPROM® II up to 20 m. In the early phase of these products the storage of the terrain data base has been realized by the well-known discrete cosine transform amplitudes (DCT), patented, [86], [87] in 1985, which is the key of the JPEG compression.

### 6.3. LASER based TERRAIN MATCHING

Dornier Luftfahrt GmbH has investigated in the 80ies the application of LASER altimeters in the field of 3D-object-detection and -recognition as well as terrain contour measurement. A patent entitled "Linear method of navigation", proposed by Metzdorff, Lux and Eibert 1990 [88], describes a method for aircraft navigation which includes sensor signal processing with reference data. The method provides for sensing and range finding the elevation profile underneath the craft. Those elevation data are fed to a segmenting and type classifying unit, whose output in turn is fed to a classifying unit. The position of the craft is determined by comparing the segmented overflown strip with corresponding topographic features from the reference information. It turned out, that the very small foot print of the LASER beam compared to the RADAR beam had two main advantages, namely the improvement of the stealth properties and a much better measurement of the terrain profile. On the one hand the LASER distance measurement has been more accurate, but on the other hand the distinction of reflexion of the LASER beam from the ground to reflexions from trees or roofs allowed extracting the true terrain profile without the classical systematic errors. It is clear, that multi-beam technologies or 3D imaging for object recognition allows segmenting the ground in a much better way than single beam technology.

### 6.4. Trends in TRN

Actually, TRN is a technology which found its application in different aircrafts (e.g. Tornado, Eurofighter and the missiles Scalp Storm shadow and Taurus KEPD 350 from MBDA). Due to the vulnerability of GPS and the stealth risk of RADAR based TRN technologies new key technologies could trigger the next technological push. LASER altimeters have been continuously improved due to better LASER modules. In addition one has improved and stabilized the time-trigger electronics. LASER imagers are key components in sense & avoid systems as HELLAS (an original Dornier development, now EADS Defence Electronics), showing outstanding ranges and resolutions in order to detect wires with a diameter of some millimetres up to 1 km distance. It is mainly a question of improving the time-of-flight measurements to get also better bad-weather capabilities, i.e. one has to replace in the future the actual LASER modules by high frequency setups in order to come from the actual analogue time-trigger method to a digital method. A considerable general progress has been made in data compression and real-time data decompression, compare e.g. JPEG and JPEG2000 on the consumer market or see a paper entitled "Telescience and interferometric metrology on the international space station" [89]. SW and RT-HW allow the handling of much bigger terrain data sets, in particular to improve the accuracy and the data age.

## 7. SUMMARY

Like in manned aviation inertial navigation systems in combination with GPS the methods have evolved to build the core navigation system of unmanned aircrafts. Vulnerability or lack of availability of GPS under certain mission conditions and the unsatisfactory drift of low-cost, rate-grade IMUs have lead to two different trends. On the one hand INS/GPS systems themselves are further improved e.g. by ultra-tight-coupling methods, multi-GNSS-signal-receivers, selective antennas or new designs of inertial sensors. Driven mainly by the automotive and consumer electronics industry, inertial sensors built in MEMS technology recently have made large progress and first MEMS based IMUs have achieved tactical grade. The request for ultra-tight-coupling of the different systems will have also an impact on industry, as often GPS-receiver/chip-manufacturers, IMU-integrators and inertial sensor manufacturers are not the same and have to find new forms of tight cooperation, opening up their product systems architectures deeply.

The other main trend is on INS/GPS-complementary sensor solutions, which are mainly the well-established terrain reference navigation and the more and more up-coming image based navigation. The idea of IBN is not new and a lot of the recently achieved implementations for UAVs including in-flight demonstrations rely on 25-year-old-algorithms! The scientific challenge now is to make the algorithms become mature under operational conditions. Hence major contributions for further improvements are expected to come from research in computer vision taking into account the real-time challenge. Also the development of better or new sensors, especially 3D (LADAR, 3D-cameras) and IR-cameras, will bring a new momentum.

The mission equipment of a UAV often requires much higher precision for position and attitude calculations than for the navigation of the air vehicle itself. Therefore the mission sensor suite may also serve in future for navigation purposes and a coupling of both systems seems to be logical in order to harvest the possible synergies. This clearly would lead to higher levels of criticality of the mission system w.r.t. certification, a challenge on which the mission equipment and avionics industry has to respond.

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