DEVELOPMENT OF A MICROCONTROLLER BASED SENSOR ACQUISITION SYSTEM FOR UNINHABITED AERIAL VEHICLES

Dennis Höse, Michael Kriegel & Axel Schulte
Universität der Bundeswehr München
Werner-Heisenberg-Weg 39, 85579 Neubiberg
GERMANY

OVERVIEW

This paper will describe an experimental environment used to evaluate and investigate new flight guidance technologies for uninhabited aerial vehicles (UAVs). Furthermore a detailed insight in the concept and the configuration of the aerial vehicles and additional embedded subsystems is presented.

1. INTRODUCTION

Future flight missions, especially in the field of military operations will be characterised by growing information demand onboard the aircraft. This information demand asks for high timeliness which shall be encountered in the military domain by using deposable sensor platforms for temporal and local reconnaissance. These platforms can be uninhabited aerial vehicles (UAVs), equipped with appropriate sensors, operating in the local environment of the manned mission component, collecting specific information based on reconnaissance assignments. In principle, these UAVs can be realised on the basis of various kinds of airframe conceptions, e.g. helicopters, fixed-wing, or even lighter-than-air, depending on the operational requirements. A possible scenario could comprise a manned helicopter with several UAVs being guided from a single human operator onboard that helicopter. Regarding the UAV guidance this claims the consideration and investigation of a vehicle to operator ratio larger than one. This typically leads to the demand that the whole system has to make use of extensive automation of some certain kind. Current automation systems can be regarded as tools or active equipment supporting the human operator to fulfil certain well defined sub-tasks. This leaves the operator in the role of the high capacity decision component determining and supervising the process. But this kind of so-called *conventional automation* (e.g. autopilot or flight management systems) does not assist the operator in performing tasks like decision-making with the aim to achieve the top-level mission goals. *Conventional automation* lacks a comprehensive understanding of the current situation and the overall work objective as well as decision-making, problem solving and knowledge processing. In order to cope with these deficiencies *cognitive automation* [1] shall be used as the underlying paradigm for further enhancements of flight guidance automation. This enables the automation to offer semi-autonomous and co-operative capabilities concerning both the UAVs and the control station. Here, the UAVs are enabled to accomplish missions semi-autonomously with respect to a given mission objective and to co-operate both with other UAVs [2] and the human operator. On this high abstraction level of automation functions the architecture and to some extent the implementation of these functions is independent from the airframe conception.

This paper shall give an overview of the activities at the Universität der Bundeswehr München (Munich University of the German Armed Forces – UniBwM) in order to provide an experimental platform for the implementation and evaluation of suchlike cognitive automation concepts. Especially, a focus on a microcontroller based sensor acquisition system as pivotal pre-requisite for the data supply of a cognitive guidance system will be given here. Requirements and design of the described components shall open a perspective of a broader use of the presented solution beyond the scope of our application, e.g. for alternative airframe designs such as lighter-than-air.

The paper describes the experimental setup and the components of our experimental system with the focal point set on a rotorcraft UAV as part of this demonstration environment and its subsystems.

2. CO²SIMA – SYSTEM SETUP

The UniBwM is developing an experimental system called Co²SiMA (Cognitive & Co-operative System for intelligent Mission Accomplishment). It comprises a mobile ground control station and several type different UAVs (rotorcraft and fixed-wing aerial vehicles). These components will be described in more detail in the following sections.

2.1. Mobile Ground Control Station

The mGCS (Mobile Ground Control Station, see FIG. 1) is based on a Mercedes Sprinter Truck used twofold: transportation of the UAVs and acting as the UAV-control station during flight operations.

FIG. 1. Mobile Ground Control Station

It is equipped with an internal electrical power supply with generator providing power to all components such as two 19” touchscreen monitors, two racks of 19” PC workstations and their peripherals.

A DECT bidirectional intercom system enables all participants, namely the operator and a necessary safety pilot as well as supporting personnel to communicate. This system also offers an interface where computer generated voice messages like status announcements or critical system information can be fed into the communication system.

The data link connection to the aerial vehicles is based on four Satelline 3AS [3] radio data link modems acting on two different frequencies (uplink and downlink). This offers a bidirectional radio data link connection for receiving telemetry from the UAVs as well as sending tele-command information. Furthermore, a digital video data link receiver enables the operator to see a live video stream from the flying vehicle.

2.2. Uninhabited Aerial Vehicles (UAVs)

The first vehicle is a fixed-wing aircraft based on a model of a PZL-104 Wilga 80 with a total wingspan of 3.3m and a length of 2.25m. It is powered with a 2 cylinder 100ccm Boxer combustion gas engine and has currently a take-off weight of approximately 18 kg.

FIG 2. Fixed-wing UAV demonstrator

For flight guidance and control the purchasable autopilot system Piccolo Plus from Cloud Cap Technologies [4] has been integrated. It allows automatic starts and landings and features a flight management system where the vehicle follows a predefined waypoint route. First flights test including automatic flight mode sections have been very promising although some controller gains still have to be adjusted. FIG 2 shows the fully integrated vehicle after several successful flight tests.

The second vehicle is a helicopter based on a Vario Benzin Acrobatic Trainer with a rotor diameter of 1.78m, driven by a combustion engine with 23ccm.

With this vehicle first sensor test flights (with a very similar avionics system described in section 3.1) have been successfully performed (see FIG 3) but due to the limited payload capacity, this vehicle will only be used as a sensor test platform in the future.

FIG 3. First rotorcraft UAV demonstrator

The successor vehicle is a custom built helicopter from XXL Modelhelicopter [5] with a rotor diameter of 2.6m driven by a 2 axle turbine engine providing an output power of 6.5kW. All components of this helicopter have been chosen to be more durable than normal radio control model parts reducing the danger of material defects due to overstressing as well as to alleviate maintenance efforts.

FIG 4. Actual rotorcraft UAV demonstrator

Currently the development of a flight guidance and control system is ongoing which is currently being tested in a hardware-in-the-loop simulation environment.

The integration of all hardware parts into an avionics box (see black box between the landing skids of the helicopter in FIG 4) has been finished and first flight tests with the vehicle have already been performed. During these flights the avionics were disabled as electromagnetic compatibility (EMC) tests had not been completed by that time. The avionic components and system concept will be described in the following chapter.

3. AVIONIC COMPONENTS AND SYSTEM CONCEPT

The avionic components needed for flight guidance and control are kept modular and several different sensors are used to measure the appropriate values. These will be described in the following section.

3.1. Avionic sensors and hardware

In order to obtain position and attitude information a Crossbow NAV 420 [6] inertial measurement unit (IMU) is used. It is a combined GPS Navigation and GPS-Aided Attitude & Heading Reference System (AHRS) using

MEMS based inertial sensors (gyroscopes, magnetometers, accelerometers) as well as a 16 channel 4 Hz GPS receiver. The raw sensor data is internally fed through a high performance Kalman Filter providing filtered positional information (WGS 84) and attitudinal information (roll/pitch angles & heading, roll/pitch/yaw rates). The output of the IMU can be customised in terms of the type of data package (3 different packages are available) and the output frequency. According to the update rate of 50Hz concerning the actuators the same data output rate was chosen at the IMU. As data output is encoded into a very small data package (38 bytes in NAV mode) the output has to be decoded by a software driver into a generic data and value format enabling the flight control system (FCS, autopilot) to process the measured helicopter state values.

Additional to the IMU a microprocessor based sensor data acquisition system has been developed in order to gain a number of other important system states and measurement which are fundamental for the semi-autonomous system to make appropriate decisions. A detailed description of the concept, the assembly and the used sensors will be described in chapter 4.

Two PC 104 embedded computers form the computational power aboard the vehicle. One of them is used as the flight control computer (FCC) running the flight guidance and control system (FCS) and the other one (MMC) will be used to run a cognitive Mission Management System based on COSA [7] enabling the vehicle to perform missions semi-autonomously. Communication between the two computers will be established using an Ethernet connection.

The aforementioned Satelline 3AS radio data link modems feature a serial interface (RS-232) and are capable of transmitting 19200 baud. Both modems are connected to a single serial port at the FCC through a Y-cable splitting the normal pin assignment into a sending and a receiving interface with disabled flow control.

The input signals for the actuators (high quality model servos) are based on PWM (pulse width modulation). Due to the limited real time capabilities of the FCC the signals are generated by a separate controller board (Pontech HBC 101). Flight control data generated by the FCS will be sent through a serial connection (RS-232) to the controller board which generates the corresponding PWM signals.

A small CCD camera is mounted at the front of the avionics box (see FIG 4 black box below the helicopter airframe). The camera is mounted in gimbals that can be panned and pitched by use of two small but very precise model servos.

3.2. Avionics software concept

FIG 5 shows the software system concept and setup of all units in the avionics system. On the right hand side the FCC is depicted running several different tasks. Central element here is a server process serving and relaying sensor and communication data. All sensor data gathered from the corresponding driver processes (IMU and µC sensor acquisition board µSAB) are buffered and are made available to the FCS as well as the communications process (COMC) for telemetry purposes.

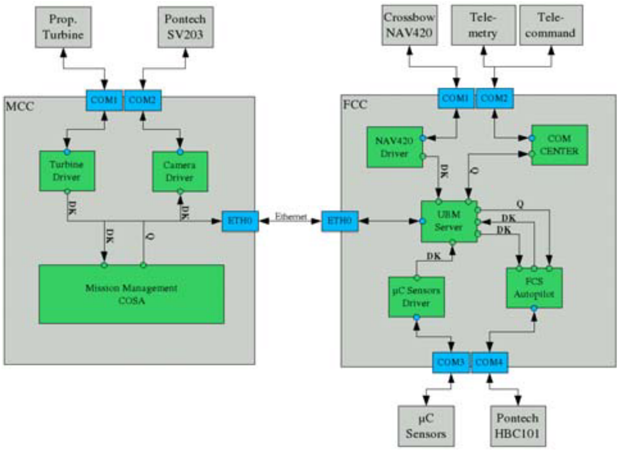

FIG 5. Avionics software concept

The COMC controls the communications from and to the mGCS. Each message is packed into a proprietary package including a 16 bit CCITT CRC (Cyclic Redundancy Check) value ensuring at a high level that corrupted data will be discarded if the received and calculated CRC values do not match. Important information like FCS controller gain values or autopilot mode changes are transmitted by using an ARQ (Automatic Repeat-reQuest) protocol including sequence numbers in order to ensure data link integrity and to increase data link performance.

On the left side the MMC is depicted running the Mission Management System. This system can control the FCS system by use of high level commands such as autopilot modes or waypoint information. It can also manage payload systems and sensor orientations like the aforementioned CCD camera as well as aircraft systems like the turbine engine through the ECU (Engine Control Unit).

3.3. Flight safety concept

In order to ensure flight safety during flight operations of the experimental system a safety pilot will act as the last instance of decision whether the vehicle flies in automatic or manual mode. In manual mode the PWM signals are generated by a RC receiver and are routed to the appropriate servos. The use of high fidelity RC transmitters and receivers such as a Graupner (JR) MC-24 and SMC 20DS offer a digital transmission and reception type based on pulse code modulation (PCM). This allows the configuration of special failsafe channels (channels 1 - 8) where the output signal of the receiver for this certain channel can be predefined in case of interference. Other channels that have not been configured to be failsafe channels remain the last properly received signal value when reception is interfered (hold function). As sending and receiving on only one frequency can be jammed or interfered very easily, the HF and DPSI TWIN system from EMCOTEC have been integrated.

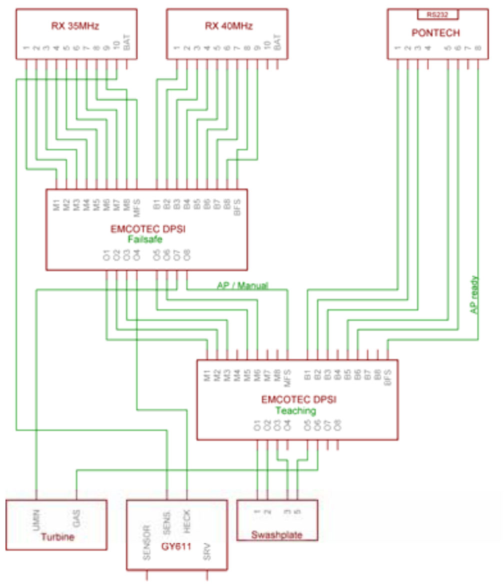

FIG 6. Flight safety signal routing

Therefore, the transmitter of the safety pilot has been modified so that it simultaneously transmits the control information on two different carrier frequencies (35MHz and 40 MHz). Onboard the UAV two receivers are installed receiving the signals which are then fed into a DPSI TWIN device. This features two input interfaces for PWM signals of a main and a backup receiver and one PWM output interface. If the active receiver gets interfered the predefined failsafe channel will output a certain signal value allowing the DPSI TWIN to detect that this receiver is currently being interfered. The consequence is that the DPSI switches to the backup receiver if its failsafe channel shows good reception. The outputs of this DPSI TWIN device are then fed into a second DPSI TWIN on the main receiver input interface. The backup interface gets its signals from the already mentioned HBC101 constituting the autopilot control commands (see FIG 6). Through a switching channel from the safety pilot transmitter fed into the interference detection channel of the second DPSI TWIN it can be defined which signals are routed to the servos (manual or automatic mode). As each DPSI additionally offers a twin power supply this cascaded configuration offers a redundant receiving installation with redundancy on part of the power supply for the receivers and the servo actuators leading to an increase in flight safety.

4. THE SENSORIC DATA ACQUISITION SYSTEM

The semi-autonomous flight guidance system shall be able to make mission and flight critical decisions with regard to the superior mission goals and if applicable even independently of the human operator. Therefore, the knowledge of as many vehicle state values as possible is crucial as what normally is being handled by a human pilot shall be taken over by automation. Hence a comprehensive acquisition of the prevailing situation onboard is necessary. For this purpose the sensor data acquisition system has been developed to gain a number of additional system states and atmospheric measurements that could not, or only with high efforts be realized with the FCC. The following sections will describe the system requirements, the configuration and used sensors to implement this sensor data acquisition system.

4.1. Requirements for the sensor data acquisition system

Especially equipment for aircraft has to meet unique requirements since failure of a subsystem or sensor can result in partial damage or even a complete loss of the vehicle. As basis of automation, sensor systems have to meet high standards. Therefore, the sensor data acquisition system has to be reliable even under harsh conditions like heavy vibrations, high variations in temperature and static air pressure changes, which are typical conditions encountered in the domain of aviation. Besides to electromagnetic compatibility (EMC) these systems additionally need to be small in component size and mass as well as featuring low energy consumption.

The desired data acquired by the system shall include the static air pressure, the ambient temperature concerning atmospheric values as well as the rotational speed of the main rotor and the current fuel consumption of the turbine concerning aircraft parameters. For monitoring purposes of the avionics system the voltage level of the avionics power supply including the actual current consumption shall be measured. For an accurate determination of the altitude of the vehicle at ground level two ultrasonic range finders shall be used and a push-button on each landing skid of the helicopter shall signal ground contact.

4.2. General overview of the system

Core element of the system is an Atmel AVR ATmega32- [8] microcontroller (µC) collecting all needed data independently from the FCC. The recorded and processed data is sent via a serial interface (RS-232) to the FCC. For convenience a plug and play display unit can be connected to the system allowing direct readout of the data for on ground testing purposes. All elements of the sensor system are shown in FIG 7.

FIG 7. Components of the sensor acquisition system

The hardware concept comprises three main elements namely the main unit, several external sensors and the display unit. The main unit contains the circuit board carrying the ATmega32 µC including all supply elements. Within the enclosure the absolute air pressure sensor (MPX4100A [9]) is placed whereas the temperature sensor (DS1631 [10]) is situated outside the box. The communication with the 16bit AD-converter (ADS1100 [11]), measuring the analog output of the static pressure sensor, the temperature sensor and the ultrasonic range finders (SRF10 [12]) is established via the two-wire serial-bus (I²C). The system layout and wiring can be seen in FIG 8.

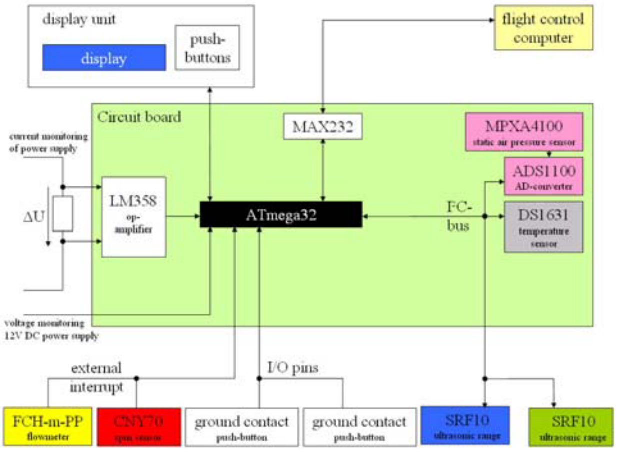

FIG 8. System layout and signal flow

The external sensors like the supersonic range finders, the main rotor revolution sensor (CNY-70 [13]), the fuel flow meter (FCH-m-PP [14]) and the ground contact push-buttons are connected via RJ45 ports, as these sensors will be mounted on various positions on the helicopter airframe. This plug type allows an easy way to customize cable lengths to the sensors and features a vibration proof electrical connection. The current fuel consumption rate is acquired by use of a flow meter FCH-m-PP and the main rotor revolution is measured by a reflection sensor CNY70 with open collector transistor output. Simple and reliable push-buttons are used as sensing devices to detect ground contact of each landing skid. Additionally the power supply system is monitored with the internal ADC (analog to digital converter) of the µC and the current is measured using a shunt circuit. In order to get a larger cooling area for the voltage regulator the front of the housing is made out of aluminum. The 3rd element, the handheld display unit (top of FIG 7), can be connected through a 25-pin D-Sub connector for direct displaying all actually measured data. Because of the hot plug and play feature the display can be used on ground for checking all sensor values especially the avionics power supply voltage and actual current consumption. Through this unit the sensor data acquisition can also be controlled by the 2 push-buttons on the right hand side of the display. For power saving mode it is possible to switch off the background via push-buttons or software.

The overall mass of the sensor acquisition data system (excluding the hand held display unit) in total is only 166 grams. The average current consumption of the system within a voltage range of 7 to 18 V DC is 70mA without and 94mA with the display unit connected.

4.3. Specifications of the used components

In this section all the sensors will be described briefly and some details concerning this project are given.

4.3.1. Microcontroller AVR ATmega32 (ATMEL)

The CMOS-8-bit-RISC-microcontroller ATmega32 with 32kbytes ISP (In System Programmable) flash memory was chosen because of several onboard features:

- 8 channel 10bit Analog to Digital - Converter (ADC)
- Two 8bit and one 16bit hardware timer
- 3 hardware PWM channels
- Hardware USART interface
- Two-wire serial interface (I²C)
- Watchdog timer
- External interrupt pins
- Low power consumption

The µC is clocked with an external 16 MHz crystal and is programmed in C-language using the freeware avrgcc compiler (made available through the GNU project) with the Atmel AVR-Studio as IDE (Integrated Development Environment).

4.3.2. Revolution detecting device - CNY70 (Vishay)

This optical sensing unit consists of an infrared LED combined with a phototransistor. A black marking at the rotor drive shaft prevents reflecting the light from the LED which leads to a high – low – high signal toggle per revolution counted by the µC using the external interrupt feature. Due to the good quality of the signal, the counting of toggles does directly take place within the µC without additional circuitry. Combined with an opaque casing of the phototransistor very reliable data is achieved without mechanically affecting the drive and main rotor system.

4.3.3. Fuel-Flowmeter FCH-m-PP (B.I.O.-TECH)

The wheel driven non-contacting Hall Effect sensor can measure fluid flows from a range of 0.015 up to 0.8 liter/min. Because of its resistance to acid it should also be resistant to kerosene. Although an accurate readout could be achieved when testing the sensor, long term tests showed that the kerosene is weakening the plastic housing. Because of the possibility of clogging the fuel flow if the wheel gets stuck, this flow meter will not be used. Another solution can be an optical fuel level monitoring system in main supply tanks which is easy to integrate and does not affect the fuel lines to the turbine. This type of fuel measurement system is currently under investigation.

4.3.4. Ultrasonic range finder SRF10 (Devantech Ltd)

This commonly used ultrasonic range finder module with an onboard controller has a measuring range from 4cm up to 6m and features a two-wire (I²C) interface. Each measurement has to be triggered by the µC and the processed data (range to next object) will then be sent back by the SRF10-controller. Performed test on various surface types showed fluctuations on grass whereas good results were achieved on concrete and asphalt. The measurement error especially at higher distances increases depending on the surface texture and the slope of the terrain. The spreading at ground level because of the grass-surface makes software techniques necessary for post-processing the data. Another encountered problem was the reception of sound waves of the preceding measurement cycle. This effect was avoided by use of a timing sequence depending on the measure distance.

4.3.5. Thermometer DS1631 (MAXIM)

The DS1631 is a digital thermometer measuring the difference between wavelengths of a temperature stable crystal and one with a high temperature coefficient. It has a maximum resolution of 0.0625 K, but because of the inaccuracy (e.g. influence of the temperature of the housing) it is limited by software to full degrees. Within the range of 5 to 28°C the discovered linearity error of almost 2°C is corrected by software. Although the sensing device is placed outside the housing the warming of the enclosure still influences temperature measurements at such a low level that this can be tolerated.

4.3.6. Static air pressure sensing device MPX4100A

FIG 9 shows the SMD-sized pressure sensor which measures the pressure difference between its evacuated reference dose and the ambient pressure. The deflection of the die is transferred via resistance strain gauges in full bridge configuration to a voltage signal. The temperature compensation is performed internally by operational amplifiers and a resistance network.

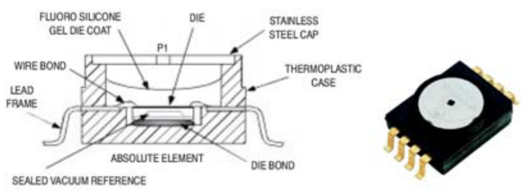

FIG 9. The MPX4100A static air pressure sensor

The output is an analog voltage signal reaching from 0.3V (200hPa) to 4.8V (1050hPa) proportional to the ambient air pressure. The analog data is fed through a low-pass filter for noise reduction with a cut-off frequency of 650Hz. Between 500m and 1500m height, the calculated theoretical resolution of this sensor has been found to be about 28cm in altitude change. Performed tests in a pressure chamber showed a very good compliance of the readouts within the range from 850 to 950hPa.

4.3.7. AD-converter ADS1100 (Texas Instruments)

The Delta-Sigma self-calibrating AD-Converter was used offering a high resolution of 16bit and its two-wire serial-bus interface. To reduce the noise characteristics an additional amplification circuit was not used.

4.3.8. Power supply monitoring

The power supply monitoring is realized by using a shunt resistor (0.01 Ohm) placed between the battery and the avionics equipment. With an expected maximum of 5 ampere current consumption required by the avionics equipment the resulting voltage difference will result in 50mV. An operational amplifier LM358 supplied with a symmetric voltage (+/-8V DC) from a MAX232 (RS-232 level converter) transfers the signal into a voltage range from 0 to 5V DC which is then measured by a multiplexed AD-channel of the µC. Additionally the voltage of the avionics power supply system is also measured by an AD-channel using a potential divider.

4.4. Software

The program starts with the initialization of the µC ports, interfaces and all attached sensors. After the initialization the µC controls the sequence of the data acquisition for several sensors whereas the main rotor revolutions and the fuel flow are triggered directly by external interrupts. All processed data is transmitted via the RS-232 Interface to the FCC. A proprietary transfer protocol was used including a simplified CRC to identify transmission errors. Sending a 2 byte configuration package to the acquisition system allows the customization and configuration of the acquisition procedure e.g. how and in what manner the ultrasonic sensors are being polled.

5. SUMMARY

It has been shown that with relatively simple means a robust and inexpensive sensor data acquisition board can be realized. This enables the flight control system as well as a mission management system to access more aircraft states and parameters resulting in better performance concerning aircraft control and decision making on part of the mission management system. Although this sensor data acquisition system has been designed and developed for use in a rotorcraft UAV it can easily be integrated into type different UAVs such as fixed-wing aircraft or even into lighter-than-air designs. Therefore, only small adjustments concerning the sensor configuration would have to be made (e.g. an additional dynamic pressure sensor for a fixed-wing aircraft). Furthermore, there are still resources left for additional features like some PWM channels that could drive additional servos. A possible application could be to extend and retract data- or video-link antennas to increase sending and receiving performance if these are situated between the landing skids of a helicopter.

For the next generation of the acquisition system a more capable µC the ATMega128 was used providing more I/O (Input and Output) ports, a second USART interface and more memory (Flash, SRAM and EEPROM). This offers room for future expansions and modifications of this sensor data acquisition system.

6. ACKNOWLEDGEMENT

This contribution originates from my diploma theses with the same title made 2006 at the professorship of flight mechanics and flight guidance at the faculty for aeronautical engineering at the University of the German Armed Forces in Munich. The thesis was, on the occasion of the First CEAS European Air and Space Conference 2007 awarded with the Zeppelin – Foundation price of the city of Friedrichshafen. I want to express my gratitude to my tutors of the thesis and the co-authors of this paper.

7. REFERENCES

[1] Axel Schulte, Claudia Meitinger & Reiner Onken (in preparation). Human Factors in the Guidance of

Autonomous Vehicles: Oxymoron or Tautology? The Potential of Cognitive and Co-operative Automation. In: *International Journal on Cognition, Technology and Work.*

[2] Claudia Meitinger & Axel Schulte (2006). Cognitive Machine Co-operation as Basis for Guidance of Multiple UAVs. In: *NATO RTO-Meeting Proceedings HFM-135: Human Factors of Uninhabited Military Vehicles as Force Multipliers.* Biarritz, Frankreich, 9.-11. Oktober 2006.

[3] Satel Satelline 3AS radio data modem user's manual; http://www.satel.com/get_file.php?file=SATELLINE_3AS_V2_7_UK_www.pdf&dir=home

[4] Cloud Cap Technologies Piccolo Plus autopilot system; http://www.cloudcaptech.com/

[5] XXL Modelhelicopters for hobby and industrial applications; http://www.xxl-modelhelicopter.de/

[6] Crossbow NAV420 intertial measurement unit users manual; http://www.xbow.com/Support/Support_pdf_files/NAV420_Users_Manual.pdf

[7] Henrik Putzer & Reiner Onken. COSA – A generic cognitive system architecture based on a cognitive model of human behaviour. In: *International Journal on Cognition, Technology and Work*. 5, 140-151. 2003.

[8] ATMEL AVR ATMega32 users manual; http://www.atmel.com/dyn/resources/prod_documents/doc2503.pdf

[9] Freescale MPX4100A, Integrated pressure sensor data sheet; http://www.freescale.com/files/sensors/doc/data_sheet/MPX4100A.pdf)

[10] Maxim DS1631High precision digital thermometer; http://datasheets.maxim-ic.com/en/ds/DS1631-DS1731.pdf

[11] Texas Instruments ADS1100, Self calibrating 16bit Analog to Digital Converter data sheet; http://focus.ti.com/lit/ds/symlink/ads1100.pdf

[12] Devantech Ltd. SRF10 Ultrasonic range finder user manual; http://www.robotikhardware.de/download/srf10doku.pdf

[13] Vishay CNY70, Reflective optical sensor with transistor output, data sheet; http://www.disam.upm.es/cybertech/Docs/General/cny70.pdf

[14] BioTech FCH-m-PP Flowmeter data sheet; http://www.bio-tech-europe.com/pdf/20070316090 522_92202924_92202924-FCH-m-PP.pdf