Sensor fusion is on the agenda

Carmakers have been using sensor fusion for years. Academics provided the theory, chipmakers offered the required software. From now on, other vehicles can use sensor fusion, too.

In general, sensor fusion is nothing new. Mother Nature uses it: snakes combine visual data from the eyes with smell information from their forked tongue and temperature information from their infrared-sensitive receptors. This is necessary to track and catch prey, because they can’t focus their eye lenses. Also in technical systems, combining data from different sensor elements and generating new information has been state-of-the-art for many years. For example, combining pressure sensors with temperature sensors allows us to evaluate the measured pressure in the sensor device. Also in technical systems, combining data from different sensor elements and generating new information has been state-of-the-art for many years. For example, combining pressure sensors with temperature sensors allows us to evaluate the measured pressure in the sensor device.

Automated driving was one of the driving forces behind the improvement of sensor fusion technologies. An example is the computing of the orientation of a car on the road’s lane or in relation to other vehicles or even pedestrians. ADAS (Advanced Driver Assistance Systems) use them heavily. How much automotive suppliers expect from the market can be seen from the investments they have made: Since 2011, for example, Bosch has employed about 5000 engineers in Palo Alto (California) and Abstatt (Germany) developing technologies for automated driving.

Automated driving affects every aspect of the car – powertrain, brakes, steering. It is based on sensors featuring radar, video, and ultrasound technology. “Sensors are the eyes and ears that let vehicles perceive their environment,” said Dr. Dirk Hoheisel, who sits on the company’s board of management.

MEMS make sensor fusion affordable

Micro-electromechanical systems (MEMS) are the building blocks of sensor fusion. MEMS-based sensors are available from different manufacturers. Low-cost MEMS for accelerometers and gyroscopes are useful for position sensing and when fused together result in pitch and roll accuracy over a broad frequency range. They can be used for dead reckoning, medical devices, robotics, and industrial machine control. A typical application is an inertial measurement unit (IMU) comprising a three-axis gyroscope, an accelerometer, and a magnetometer. The IMU needs to fuse the data of the sensor elements. MEMS are also used for attitude and heading reference systems (AHRS). Magnetic distortion problems caused by steles, permanent magnets, or electric currents have been solved in the last years.

Different fusion methods exist: the evaluated average, Bayes’ theorem (see insert “Bayes’ theorem”), the Kalman filter (see insert “Kalman filter theory”), Fuzzy algorithms, and least squares. All of them require computing power by means of Floating Point Units (FPU) or Digital Signal Processors (DSP).

Figure 1: The iNemo-M1 is a 9-axis sensor module combing gyroscope, accelerometer, and magnetometer with a 32-bit micro-controller running the sensor fusion software developed with the iNemo software suite (Photo: ST-Microelectronics)

Figure 2: The LPMS-CU is an inertial measurement unit and attitude heading reference system comprising three different 3-axis MEMS (gyroscope, accelerometer, and magnetometer), which provides CAN connectivity (Photo: Life Performance Research)
The Autonet 2030 project, supported by Hitachi and the Technical University of Chemnitz (Germany), has developed a multi-sensor fusion concept for plausibility checking of vehicle-to-vehicle communication by vision-based multiple object tracking. The project uses a Mobileye front camera and an Atheros AR541A-B2B-based communication device. Moreover, this data is fused with the yaw rate and velocity data from the CAN in-vehicle network. The probabilistic data fusion among these sensors is implemented with the Baselabs framework for ADAS.

**Software support from chipmakers**

Sensor fusion is based on software. Sensor data has to be combined for example to calculate accurate positions and orientations. Sensor fusion software runs on normal MCUs that often provide CAN connectivity. Today’s 8-byte payload limitation of CAN messages will no longer be a limiting factor when CAN FD hardware with up to 64-byte data fields becomes available. Chipmakers are committed to sensor fusion and have developed dedicated software packages.

Sensor fusion algorithms are important to compensate undesired effects. For accelerometers in AHRS, for example, there is no difference between gravity and lateral acceleration. Lateral acceleration needs to be properly compensated, otherwise the roll and pitch values are incorrect. Sensor fusion algorithms also need to detect magnetic distortions.

Freescale provides the Xtrinsic suite of sensor fusion tools for its ARM-based Kinetis MCU family featuring CAN connectivity. The current version is based on the CodeWarrior software development environment. Users can download a free node-locked version for evaluation and development. With pre-compiled sensor fusion application templates, users can experiment before beginning the application software development.

**Kalman filter theory**

Kalman filtering is a recursive algorithm, which is suitable for the fusion of noisy data. It estimates the state of a system at a time by using the state of a previous time. A common application is sensor fusion for navigation and guidance of vehicles. The Kalman filter calculates estimates of the true values of states recursively over time using the measured values and a mathematical process model (transition and observation matrices). Kalman filters are also used in robot motion control applications. The algorithm works in a two-step process. In the prediction step, the Kalman filter produces estimates of the current state variables, along with their uncertainties. Once the outcome of the next measurement (necessarily corrupted with some amount of error, including random noise) is observed, these estimates are updated using a weighted average, with more weight being given to estimates with higher certainty. The Kalman filter can be regarded as a simple dynamic Bayesian network (see insert “Bayes’ theorem”).

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Figure 3: The PCAN-GPS is a CAN-connectable sensor module based on NXP’s LPC4000 micro-controller comprising a GPS receiver, a magnetometer, an accelerometer, and a gyroscope (Photo: Peak-System Technik)

ST-Microelectronics offers the iNemo engine software suite, which comprises filtering and predicting algorithms. This includes algorithms to integrate outputs from multiple MEMS sensors. The software can be used with iNemo inertial modules to create multi-axis MEMS sensor solutions for motion and heading recognition. Equipment manufacturers across different market segments can deploy motion detection systems with up to 10 degrees of freedom, comprising 3-axis sensing of linear, angular, and magnetic motion with barometer/altitude readings from a pressure sensor. Of course, the software supports Kalman filtering. The generated firmware runs on STM32 micro-controllers.

Atmel has partnered with sensor manufacturers and sensor software providers. The result is the Sensor Hub Solution software suite, which can be used in conjunction with Atmel's development tools suitable for its Cortex-based processors. Renesas offers the RX Sensor Fusion kit. It comprises an RX62N RDK micro-controller evaluation board, a Gyro board, Sensor Fusion demo, and GUI code as well as application notes. The kit is designated for position sensing applications.

In some sensor fusion applications, FPGAs (field programmable gate array) are used. Therefore, Altera has developed special functions for sensor fusion devices. This includes camera, radar, and ultrasonic functions. System-on-Chips (SoC) featuring sensor fusion will grow with an annual rate of 60 percent, predicted Semico Research. This growth will result in about 2.5 billion units in the year 2016, mainly used in smartphones, tablets, and digital cameras.

Texas Instruments has published an application note [6] for a 9-axis sensor fusion using the direction cosine matrix (DCM) algorithm on the MSP430F5xx processor family. The report explains the implementation of an AHRS, which is based on magnetometers. The calibrated sensor values are fed to the DCM algorithm in order to calculate the roll, pitch, and yaw values (Euler angles). Using a CAN connectable micro-controller, these values can be sent to other ECUs.

Software support means mainly tools. Baselabs provides a hybrid approach for ADAS data fusion algorithm development. The hybrid development offers a way to combine the advantages of model-based and code-based solutions. Baselabs tools support data logging and handling as well as the development of algorithms for data fusion. They are an alternative to Simulink (model-based) or to Matlab (code-based). Baselabs tools need less set-ups, claims the provider.

Integrating smartphones

Besides chipmakers, other parties are also developing sensor fusion software. Some OEMs and chipmakers are cooperating with universities to develop such software suites. There are also new sensor fusion applications for passenger cars. The University of Paderborn has developed a smartphone-based navigation system using speed information from the CAN in-vehicle networks. The researcher connected an Android phone via a Bluetooth-to-CAN gateway to the in-vehicle network. The sensor fusion was carried out by an error-state Kalman filter, whose complexity was reduced to achieve real-time operation. Several carmakers (Daimler, Ford, and General Motors) have considered integrating smartphones into the car’s electronic control system. General Motors has proposed the Autolog programming framework [1]. Experimental results have shown that the latency could be reduced by the factor four to seven, relative to a not optimized solution. Autolog uses Datalog to express sensor fusion, but incorporates some optimization methods, which minimizes bandwidth usage and latency problems.

Security needs to be considered

Security is an issue in mission-critical applications. Last year, the University of Pennsylvania presented its attack-resilient sensor fusion concept. The researchers studied a shared bus, such as CAN, on which messages are broadcasted. They investigated the effects of communication schedules on sensor fusion performance. In addition to the simulation, the researchers used a Land Shark robot with four sensors. This robot is commonly used in hostile environments to save injured people or carry cargo. It has four...

Bayes’ theorem

This theorem deals with the relation of a current probability to the prior probability. The interpretation of Bayes’ theorem varies. In the Bayesian interpretation, the probability is based on the degree of belief. The other interpretation relies on the proportion of outcomes. The Bayesian approach has been used for example for a multi-sensor pedestrian detection system [A]. In the simplest case, a Bayesian network is specified by an expert and is then used to perform inference. In more complex cases, it is not possible to define a model. In this case the network structure and the parameters of the local distributions must be learned from the data.

[A] L. Ngako Pangop and others: A Bayesian multi-sensor fusion approach integrating correlated data applied to a real-time pedestrian detection system, IROS workshop 2008.
sensors that estimate its speed – GPS, two encoders, and a camera. “We assumed that at most one sensor can be attacked at any given point of time. In addition, while it is true that some sensors are easier to spoof than others, we assumed that any sensor can be attacked in this scenario; if it is known which sensor is being attacked then any schedule that places that sensor first would result in a smaller fusion interval,” explained the researchers. They proposed a communication schedule, namely the Ascending schedule, which aims to minimize the attacker’s capabilities by either providing little information (sending at the beginning of the schedule) or little power (larger intervals). Of course, more research is needed on how to secure sensor fusion. The reported study assumed uncompromised sensors that always provide correct measurements. An extension of random faults in addition to attacks has to be the next step.

Applications are not limited to cars

Sensor fusion is not limited to mobile computing equipment such as smartphones and tablets or road vehicles. Application opportunities can also be found in mobile machines including precision farming applications and mobile robots. One example is the fusion of sensor data for moving robots: gear and force data are fused to Cartesian leg force data, which is combined with positioning information, resulting in a total force vector.

The California Polytechnic State University has developed a sensor fusion application for a low-cost truck collision avoidance system. The focus of this sensing system is to prevent rear impacts and sideswipe crashes. A system that provides coverage for these crash modes requires the use of both short range and long range sensors. Ultrasonic and magnetic sensors provide lateral blind-spot detection, while a radar sensor monitors the rear. The following sensors were selected: the HMC2003 three-axis magneto-resistive sensor by Honeywell, the LV-MaxSonar.EZ ultrasonic sensor by Maxbotix, and a radar sensor with CAN interface. A mathematical model was created to understand the behavior of the magnetic signal as a vehicle passes the sensor. This model includes the effects of magnetic field strength, vehicle dimensions, and the number of acting dipoles. The model can be used to set numeric values for various object types. A Bayesian recursive model was created to convey the likelihood of a vehicle being present in the lateral blind zones of a large truck. The algorithm helps to integrate multiple sensors. By knowing the advantages and limitations of each sensor, the algorithm can help alleviate false positives that may arise with the use of standalone sensors.

In complex applications, sensor data are available in different CAN-based networks which are not synchronized. One of the options is to use the TTCAN protocol as defined in ISO 11898-4. Combined with the CAN FD data link layer protocol, this approach provides sufficient bandwidth and may avoid patent infringements (e.g. with US8504864), if all networks use the very same global time reference.
**CAN products ready-to-go**

In particular for low-volume applications, off-the-shelf sensor fusion products are needed. The first companies have developed such products. Smart Microwave Sensors offers the Bumper-08xx electronic control unit for experimental vehicles. It collects data from different sensors (range, angle/position, radial speed, reflectivity level, etc.) and fuses them. Alternatively a PC with CAN connectivity can be used for data fusion. The Drive-Recorder software supports sensor fusion.

Low-cost is a demand. The Swiss U-Blox company has developed a sensor fusion dead reckoning system in cooperation with ETH university in Zurich (Switzerland). The UBX-M8030-Kx-DR chip includes a sensor fusion engine that blends data from satellites with wheel tick, gyroscope, and accelerometer data from the CAN in-vehicle network. This chipset is able to accurately track a vehicle’s position during the drive of a 5-story park garage with multiple 360-degree turns. The car used in this test was an Opel Astra. The system comprises a low-cost single-frequency GNSS receiver and a MEMS gyroscope with wheel tick sensor. On the basis of tick and gyroscope measurements from a single wheel, the vehicle speed and heading rate can be calculated. In order to achieve optimal dead reckoning performance, the GNSS and sensor measurements are combined using a tightly-coupled extended Kalman filter allowing for a continuous and automatic calibration of unknown sensor parameters, such as bias and scaling factor of the gyroscope and the scaling factor for the wheel ticks representing the wheel’s radius. Since the temperature dependent drift of the gyroscope bias during GNSS outages can degrade the dead reckoning performance significantly, temperature and gyroscope bias are simultaneously measured while the vehicle stands still and the Temperature Compensation Table (TCT) is updated continuously. Future developments of MEMS gyroscopes with improved measurement stability and sensitivity will broaden the application area further.

Life Performance Research (Japan) has developed the LPMS Motion Sensor, which consists of a miniature IMU and an AHRS. It uses a 3-axis accelerometer, gyro and magneto sensors, and an integral Kalman filter. The product supports update rates of up to 500 Hz and comes optionally with a CAN interface. It can be used for motion capturing and vehicle dynamic applications. For the CAN interface, which is able to run at 1 Mbit/s, optional CANopen support is available. However, there is no standardized CANopen framework or profile available for devices featuring sensor fusion capabilities.

Quanergy Systems (USA) has developed an ADAS system using Lidar (Light Detection and Ranging) laser sensors. They are linked to the Tegra 1 processor via Ethernet. The processor by NVIDIA is the heart of the data fusion engine, which is connected to the CAN in-vehicle networks. Via CAN the unit receives velocity, acceleration, and brake pedal position values as well as other data available on the OBDII on-board diagnostic interface. The resulting data shown on the head-up display or the vibration commands for the steering wheel and the seat are communicated via CAN as well as other auditory cues (beeps and vocal commands).

Peak (Germany) offers the PCAN-GPS module, a programmable sensor unit for position and orientation determination. It features a satellite receiver, a magnetic field sensor, an accelerometer, and a gyroscope. The sampled data can be transmitted via CAN and logged on the internal memory card. The data is processed by a NXP LPC4000 micro-controller. Using the supplied library and the Yagarto GNU ARM tool-chain (contains the GNU Compiler Collection GCC for C and C++), application firmware can be created and then transferred to the module via CAN. This includes options to manipulate, evaluate, filter, and route the data. PCAN-GPS is provided with a demo firmware that transmits the raw data of the sensors periodically via CAN. The source code of the demo firmware as well as further programming examples are part of the delivery.

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**Holger Zeitwanger**

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**Literature**


[6] Erick Macias and others: Nine-axis sensor fusion using the direction cosine matrix algorithm on the MSP430F5xx family

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