

Sensor fusion: Inertial measurement units

An IMU embeds several sensors on the same physical device. Combined sensor data tailored for a certain application is available on a CAN interface. This unburdens the CAN network from additional traffic and allows a simpler network design.



(Source: Adobe Stock)

An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and orientation. It works by detecting linear acceleration using accelerometers and rotational rate using gyroscopes. Some IMUs also include a magnetometer, which is commonly used as a heading reference. Such IMU configurations contain one accelerometer, gyroscope, and magnetometer per axis for each of the three vehicle axes: pitch, roll, and yaw. As a rule, an IMU is equipped with a CAN interface. On the market devices with 9 DOF (degree of freedom) or 6 DOF (without magnetometers) are available. IMUs are essential components in robotics, diverse vehicles, manned and unmanned aircraft (e.g. drones), spacecraft, satellites, ships, submarines, etc.

Included in GPS (global positioning system) devices an IMU allows a GPS receiver to work when GPS signals are unavailable e.g. in tunnels, inside buildings or when electronic interference is present. The IMUs are often incorporated into inertial navigation systems (INS), which use the IMU data to calculate attitude, angular rates, linear velocity and position relative to a global reference frame. Thus, INS form the backbone for the navigation and control of many commercial and military vehicles. Simpler INS versions termed AHRS (attitude and heading reference systems) utilize IMUs to calculate vehicle attitude with heading relative to magnetic north. Here, the data collected from the IMU's sensors allows a computer to track a craft's position, using the so-called dead reckoning method.

In land vehicles, an IMU may be integrated into GPS-based automotive navigation systems or vehicle tracking systems. This gives the system a dead reckoning capability and the ability to gather data about the vehicle's current speed, turn rate, heading, inclination, and acceleration. In combination with the vehicle's wheel speed sensor output

and the reverse gear signal the IMU data is used for traffic collision analysis.

IMUs serve as orientation sensors in smartphones and tablets. They are also used to measure motion in sport technology (e.g. fitness trackers), remote controls for gaming systems, and animation applications. The IMU is essential in the balancing technology used in the Segway personal transporters. Low-cost IMUs have enabled the proliferation of the consumer drone industry.

IMUs in unmanned aerial vehicles

In unmanned aerial vehicles typically the 9-DOF IMUs are used. An IMU measures the inertial quantities of a vehicle as accelerations and angular velocities. The measured values may be used for automatic feedback control loop or processed to estimate the attitude (roll, pitch, yaw or quaternion) of the vehicle. Accelerometers sense all applied accelerations also those due to vibrations or maneuvers. Thus, isolation and an accurate calibration are important. Gyroscopes measure the rotational velocity around their axis. This value may be used to estimate actual tilt angle and serves as a signal for feedback control loops e.g. for stabilization of RC helicopters.

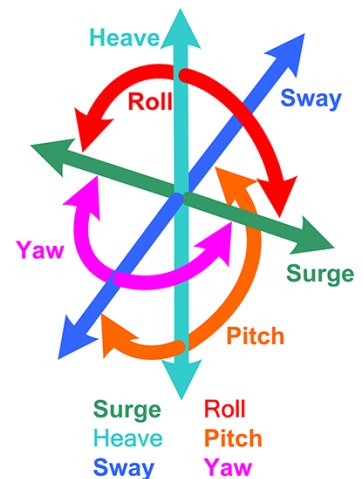


Figure 1: Six degrees of freedom (Source: Honeywell)





Figure 2: Openimu300ri IMU for a wide range of applications (Source: Anceinna)

Gyroscopes should be calibrated before each vehicle starting. A magnetometer measures the local magnetic field components, which may be compared with the world magnetic field model in order to estimate the attitude, and thus the heading respect to the local magnetic North. As the local magnetic field is easy to affect (e.g. by electric lines, sun activities, or other sensors) the local declination has to be considered while measuring.

More safety for autonomous vehicles

In an autonomous vehicle, CAN is used to pass IMU data to the main vehicle control and to share it with other vehicle sub-systems such as lidar, camera, radar, etc. The IMU application may also listen to other messages on the network. For example, the dynamic tilt algorithm supported by the IMU could be performance-enhanced by listening to messages such as odometer or vehicle speed to better compensate for the influence of linear acceleration on dynamic roll and pitch.

One of the CAN-enabled 9-DOF IMUs is the Openimu300ri by Anceinna. The Mems-based (micro electro-mechanical system) device also provides an EIA-232 interface. The ARM Cortex M4 CPU (central processing unit) runs standardized and customized algorithms created with the company's free, open-source developer tool-chain. In the INS navigation application, GPS sensor data inputted via the EIA-232 interface is fused with the IMU data for the GPS/INS sensor fusion. The IMU supports 11-bit and 29-bit CAN-Identifiers. Consumer automobiles often use customer-defined messages with 11-bit CAN-identifiers, whereas heavy-equipment vehicles more commonly use the 29-bit CAN-identifiers and define messages according to the J1939 standard. The IP67-rated IMU is designed for use on 12-V and 24-V vehicles.

INS and GNSS (global navigation satellite system) developers not familiar with CAN may use a CAN analyzer to get started with the development. The company provides an open-source Python test application that allows to read

and parse messages from IMU over CAN. A set of messages for accelerations, rates, and other data of an IMU may be defined. A DBC (data base CAN) file is then created to describe the chosen encoding of a CAN message.

The mentioned IMU application may be also used in a J1939 network. It provides the PGN (parameter group number) 61485 and PGN 61482 for acceleration and angular rate respectively. The company also supports a dynamic tilt algorithm, which computes the dynamic inclination (i.e. roll and pitch) by integrating the angular rate sensors to angle and then using the acceleration channels to establish a stable, absolute reference with respect to gravity as well as correct for the long-term drift of the integration process. The J1939 slope sensor 2 information message (PGN 61481) is used to encode dynamic roll and pitch.

The unit is dedicated for autonomous off-road, construction, agricultural, and automotive vehicle applications. It allows engineers to optimize an attitude, navigation or other algorithm for their vehicle or application and to run it in on the IMU. This minimizes communication on the CAN network and unburdens the processor, or allows to use a less expensive processor. The processed IMU data may be used for such applications as keeping a cab level, returning an arm to a specific position, keeping a bucket stable while traveling, locking out control for safety applications, supplementing GNSS data to keep a tractor on course, etc.

For construction and mobile machines

Honeywell's Tars-IMU (transportation attitude reference system) with 6 DOF is designed for heavy-duty and off-highway transportation applications. The device reports key data required to automate and monitor movements of vehicle systems and components using a sensor fusion algorithm. Communication to the vehicle is carried through a CAN interface with J1939 connectivity. The CAN bit-rate of 250 kbit/s is used. A 120-Ohm termination resistor is not included with ▶

Abbreviations used

AGV	automatic guided vehicle
AHRS	attitude and heading reference systems
ASIL	automotive safety integrity level
DBC	data base CAN
DOF	degree of freedom
ECU	electronic control unit
GNSS	global navigation satellite system
GPS	global positioning system
GUI	graphical user interface
HLP	higher layer protocol
ICE	internal combustion engine
IMU	inertial measurement unit
INS	inertial navigation systems
Mems	micro electro-mechanical system
OEM	original equipment manufacturer
PGN	parameter group number
ROS	robot operating system
TARS	transportation attitude reference system
TOF	time-of-flight

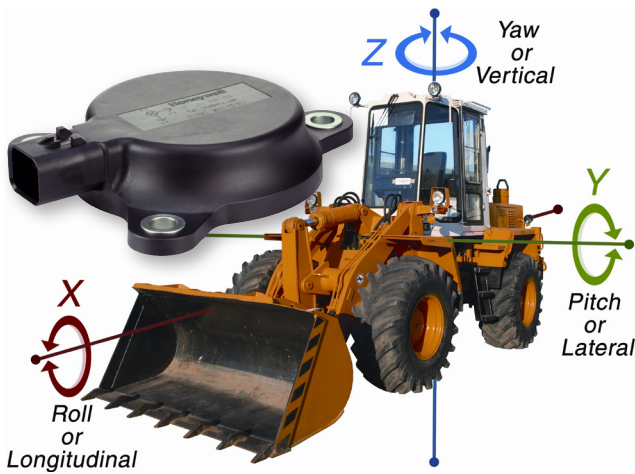


Figure 3: Honeywell Tars-IMU used in a front-loader (Source: Honeywell)

the IMU. With the IP67/IP69K-rated thermoplastic housing and an operating temperature range of $-40\text{ }^{\circ}\text{C}$ to $+85\text{ }^{\circ}\text{C}$ it is fitted for use in harsh environments. Two sensor models for 5-V and 9-V to 36-V power levels are available.

Construction vehicle OEMs (original equipment manufacturer) enable the equipment with intelligence and autonomy for certain functions to assist the operator. For example, to dig hundreds of post holes precisely placed in several rows a backhoe with an auger attachment was equipped with the Tars-IMU. In this project, the unit monitored vehicle and implement positions. In addition, it measured the alignment with the ground. An on-board system and graphical user interface (GUI) compared the information coming from the IMU and the site plan for the required holes. This allowed the operator to drive to a hole location, align the tool to specification, and dig the hole to required depth. According to the IMU supplier, construction industry moves toward fully-autonomous systems.

When designing systems for off-highway vehicles (e.g. wheel loaders), engineers need to know how the vehicle reacts in a given loading and movement situation. When installed on a vehicle, the Tars-IMU reports if a vehicle is turning, moving uphill, tilting about its lateral axis, and accelerating. This information serves as an input to systems monitoring traction and vehicle output. For example, an operator has applied power to move the vehicle. This signal is controlled and relayed by the vehicle's electronic control unit (ECU) to the engine to provide power to the drivetrain and to move the wheels. Meanwhile, the IMU is sensing the vehicle's movement. If the signal from the IMU does not match with the ECU-expected vehicle movement, it could be interpreted as a traction loss or as a wheel slippage event. If programmed to automatically reduce power to the wheels on such an event, the system could limit the incidents of wheel slippage. In some cases, wheel slippage on previously worked surfaces and ground may quickly require costly rework. The manufacturer also offers the CAN-capable 6-DOF IMU sensors 6DF-1N2-C2-HWL and 6DF-1N6-C2-HWL. For communication the J1939 protocol is used.

Devices from the JD sensor series by ifm Electronic embed a six-axes (6 DOF) IMU with a 3D-gyroscope and a 3D-acceleration sensor. Measured data is provided via a CANopen interface. The unit with sensor fusion filters determines the basis inclination values. The data of the gyroscope

corrects the influences caused by acceleration, vibration or impact. The devices reach a static precision of $\pm 0,3\text{ }^{\circ}$ and a dynamic precision of $\pm 0,5\text{ }^{\circ}$ in moving systems. The integrated CANopen interface complies with the CiA 410 application profile for inclinometers. It is used for transfer of the measured values and for sensor parameter setting. An integrated terminating resistor may be activated via software. The IP67 or IP69K protected devices with aluminum housing may be mounted horizontally or vertically. The sensors with the operating temperature range from $-40\text{ }^{\circ}\text{C}$ to $+85\text{ }^{\circ}\text{C}$ are designed for detection of inclination angles and positions of mobile machines. Typical applications are horizontal levelling of platforms or boom measurement on wheeled excavators.

Integration in robotic solutions

A robot has to fulfill such operations as to sense, to think, and to act. The Robokit platform by TDK offers such operation blocks. For sensing, the platform includes the 6-DOF IMU ICM-42688-P from Invensense, a pressure sensor, a magnetometer, a temperature sensor, as well as ultrasonic Chirp TOF (time-of-flight) sensors for 3-D sensing of the surroundings. For thinking, a Cortex M7 processor runs algorithms to drive the intelligence of the robot. For act operation, a CAN network interconnects mentioned devices with the motor controllers from Micronas. The motor controllers use an ASIL-A-ready firmware and configuration tool by Newtec. The platform software runs the ROS (robot operating system). ROS-ready drivers for IMU and ultrasonic range sensor are available. Invensense, Chirp, and Micronas are members of the TDK group.

TDK and Qualcomm Technologies announced the compatibility of the Robokit with the Qualcomm Robotics RB3 platform. Here, TDK provides the CAN-capable sensing and acting solutions. Qualcomm enables the thinking operation using company's SDA845 processor. Main applications of the platform are industrial robotics, consumer robotics, and drones.

Designed for light vehicles

The Italian company E-Shock offers CAN-capable inertial measuring units with six degrees of freedom (6 DOF). Bit-rates of up to 1 Mbit/s and 11-bit CAN-Identifier are supported. The E-Lean Advanced IMU is designed to provide estimation of vehicle attitude in terms of roll, pitch, and side slip angles based on a data fusion algorithm. The E-Shark IMU is equipped with a 16-bit micro-controller with digital signal processing unit and a GPS. It provides



Figure 4: JD sensor series (Source: ifm Electronic)

Overview of described IMUs

Company	IMU name	DOF number	HLP protocol
Anceinna	Openimu300ri	9 DOF	Proprietary or J1939
Basecam (sensor Invensense)	CAN IMU	6 DOF	Proprietary
Epson	M-G550PC2	6 DOF	CANopen
E-Shock	E-Lean Advanced E-Shark	6 DOF	Proprietary

position, heading, and speed of the vehicle. Target vehicles range from motorbikes and cars to light ICE (internal combustion engine) and electric autonomous vehicles.

E-Lean-Race-Pro IMU is specifically designed for racing applications. Due to its milled IP67-rated aluminum housing adoption in heavy-duty applications is possible as well. Connected to the vehicle's CAN network the IMU receives the vehicle speed information and provides the acceleration signals (A_x , A_y , A_z), the angular rate signals (W_x , W_y , W_z), the estimation of the vehicle's attitude, and the diagnosis status of the hardware. The unit is used in two-wheeled and four-wheeled vehicle applications. These include slide out and low-side identification (motorcycles), rollover identification (cars), traction and braking control, suspension and stability control, adaptive lighting, airbag triggering, as well as energy management, and range prediction in electric vehicles.

IMUs for diverse applications



Figure 5: The Robokit platform (Source: TDK)

LPMS-Canal2 motion sensor by LP-Research is a nine-axis (9 DOF) IMU and AHRS with CAN connectivity. Orientation data measurement around three axes is achieved using three separate Mems-sensors (3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer). The unit contains a 32-bit digital signal processor running the calculations on-board

in real-time. The CAN interface supports CANopen or a customized LP-CAN higher-layer protocol. The amount of measurement data transmitted via CAN is configurable using the LPMS-Control data acquisition software. Device configuration via CAN from a Windows PC requires a Peak CAN-to-USB interface, which is not included with the sensor. The company also offers the LPMS-CU2 9-axis IMU and AHRS with CAN and USB (version 2) connectivity. The unit performs orientation and relative displacement measurements. Additionally, temperature and barometric pressure sensors allow altitude measurements. CAN interface-related features are the same as for the LPMS-Canal2. Both IMUs are dedicated for robotic manipulator forward kinematics control, automotive dead reckoning,

object orientation tracking as well as automatic guided vehicle (AGV) navigation.

The CAN IMU from Basecam works with the company's SimpleBGC 32-bit Extended and BasecamBGC Pro controllers. Storage of calibration data is possible. The unit integrates the 6-DOF sensor ICM20608 from Invensense. I²C and UART interfaces may be used for the external device connectivity. The board size is 25 mm × 25 mm and it is optionally available in a box version. For proper functionality of the IMU, the firmware version 2.61b2 or above is required. Firmware upgrade may be done via a CAN-to-PC interface using the SimpleBGC32 graphical user interface.

IM-1 by Techmor (USA) is a 6-DOF IMU with CAN connectivity. It measures accelerations of up to 18 g and angular rates of up to ± 150 °/s on three axes respectively. Each axis measurement is provided as a 16-bit value. The three-grouped acceleration values and the three-grouped angular rates are transmitted in a corresponding CAN message each. With its compensated temperature range of -40 °C to +105 °C and the sealed Autosport connector by Deutsch the unit may be used for vehicle testing, motion tracking, navigation, stability control, and in autonomous vehicles.

Epson offers the M-G550PC2 IMU with six degrees of freedom (6-DOF) measuring tri-axial angular rates of ± 150 °/s and linear accelerations of ± 5 g. The device provides a CANopen interface according to CiA 301 (CANopen application layer and communication profile) and supports the CiA 404 CANopen device profile for measuring devices and closed-loop controllers. Bit-rates up to 1 Mbit/s are supported. The IP67-protected IMU is packaged in a dust-proof metallic case suitable for use in such applications as motion and vibration measurement, platform stabilization, attitude detection for unmanned systems, as well as vibration control and stabilization. ◀

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