Electric propulsion demonstrator for a battery-powered aircraft

Figure 1: Technicians at Scaled Composites in Mojave (CA) install a wing designed for electric motors onto a Tecnam P2006T to form the X-57 Maxwell battery-powered plane (Source: NASA)

NASA and several partner firms led by Empirical Systems Aerospace have worked on the X-57 Maxwell electric propulsion demonstrator, which uses several CANopen networks.

The X-57 is an experimental aircraft designed to demonstrate improved aircraft efficiency with a 3,5-times aero-propulsive efficiency gain at a "high-speed cruise" flight condition for comparable general aviation aircraft. In the first testing, some battery issues were detected. After fixing them, NASA has now approved the final of four planned phases of the X-57 program. These will include mounting the high-aspect-ratio wing, installing the high-lift and cruise motors, and performing flight demonstrations by late 2018 and early 2019.

The X-57 CAN-based command network is used to control the electric motors and provides aircraft health and status information. The higher-layer protocol complies with CANopen. Some connected devices transmit proprietary messages (CAN layer-2 approach). The command flow consists of throttle encoders (TEs), which digitize the existing Tecnam throttle lever positions and the electric motor controllers, which use this position as a torque target.

The NASA researchers selected the CAN protocol, because if offers various benefits including error detection, frame arbitration, multicast reception, and prioritization [1]. The configured CAN bit-rate is 1 Mbit/s. The CANopen application layer (CiA 301) was chosen because it enables the integration of CAN devices with proprietary messages.

The devices of the CANopen command network were selected based on robustness and interoperability. Because some devices use the CANopen application layer, precautions were taken to ensure the devices using proprietary messages do not interfere with the additional functionality of the CANopen devices. The CANopen protocol uses a portion of the ID field, four most significant bits of the 11-bit identifier, to indicate PDO and SDO protocols. By considering the PDO identifiers used by CANopen, and carefully selecting the IDs for proprietary messages, ID collisions were prevented.

Connected devices

The battery management system (BMS) is a custom solution built by Electric Power Systems (EPS). It uses the CANopen application layer with a customized profile to fit the X-57 CAN architecture. The BMS provides battery health and status information to the CANopen network, which can help convey relevant information to the pilot.

The CMC device is a custom solution provided by Joby Aviation (Santa Cruz, CA) and uses a CAN interface without CANopen. It controls the 10-kW lift motors and the 60-kW cruise motors. This distributed electric propulsion generates enough lift by blowing over the top of the wing to enable the airplane to take off. The motor controller communicates via CAN health and status information for itself and the motor, including torque, speed, and temperatures, that can be used to provide situational awareness to the pilot.

Motec's (Australia) synchronous versatile input module (SVIM) is an analog-to-digital converter that transmits the data on a CAN network. These modules collect data at high rates (5000 samples per second) and high resolution ▷

CAN-based battery management system

NASA and Empirical Systems Aerospace (ES Aero) selected Electric Power Systems (EPS) to supply the Energy Storage System (ESS) for the X-plane project dubbed the X-57 Maxwell. The objectives of the project are to reduce the energy consumption of the aircraft by deploying a distributed all-electric propulsion system. EPS provided the battery modules and the BCC-701 battery management system.

"We are thrilled to work with NASA, ES Aero, and the other industry partners on this ground breaking project," said Randy Dunn from EPS. "Our modular BCC-701 battery management system and its aviation grade Energy Producing Ion Core (EPIC) battery modules enable NASA to meet its objectives of having a highly reliable custom high-voltage battery." The system selected is suited for the NASA project as the BMS can quickly be configured to multiple chemistry types while maintaining the integrity of a DO311 design base. The BMS features three CAN interfaces, which report the status on every part of the system. It also sends warnings and potential problem information with the cells via the CAN networks.

(15-bit) synchronously with other modules as needed. For the X-57 application, these modules are used to record the blade pitch angle and temperatures associated with the CMCs and the motors. The size and capability to transmit on the CAN network make these devices useful in an EMI environment research capacity.

The Australian company also supplies the D175 full-color, customizable display. It is the main human machine interface between the pilot and the CANopen command bus. These screens show health and status information from the BMS, CMC, and TEs devices while also showing warnings and alarms based on the values from these devices. The screens are toggled with switch inputs incorporated into the display. Along with the situational awareness provided by this display, the screens provide additional information that aid in troubleshooting on the ground and quickly diagnosing problems in the air. The two main pages for the pilot are toggled using a simple switch, while an eight-position rotary switch enables access to the remaining pages. This setup allows 16 different pages with information about the health and status of various X-57 components.

The advanced central logger (ACL) by Motec works as the processor for the display. The logger collects all of the relevant signals, performs mathematical operations on them, and feeds the results to the display. As such, the logger is used to determine the health and status of the battery and motors and to provide any alarms or warnings to the pilot by way of the display. The ACL also controls the light-emitting diode (LED) lights on the D175 display that provide quick information to the pilot, such as battery state-of-charge (SOC) or emergency location. Finally, the ACL serves as the interpreter for the SVIMs. The SVIM transmits data via CAN in a proprietary format that is not easily interpreted by the instrumentation stack. Therefore,

Figure 2: The embedded CAN networks in the X-57 Maxwell battery-powered aircraft use fiber-optic cables to reduce the susceptibility radiated EMI from the traction power bus (Source: NASA)

data that come from the SVIM are read by the ACL and then retransmitted to the command bus for the instrumentation stack to record. Since the instrumentation stack time-tags all the data being recorded, there is an inherent delay between the time when the SVIM transmits the data and the instrumentation stack records the data after ACL retransmission. This delay is acceptable because of the slow rate of change of the data being collected by the SVIM.

The two rotary throttle encoders by Baumer (Switzerland) are CANopen compliant. These devices measure rotation of the stock Tecnam throttle levers and put the data on the CAN network. Each device also has dual encoders to provide greater reliability.

Western Reserve Controls (WRC) located in Akron (OH) supplied the fiber optic bus extenders (FOBE). They were customized for X-57 by repackaging for fit and robustness requirements. These bus extenders convert the electrical signals on the copper CAN network to optical signals on fiber optic cables and convert them back to electrical signals on a copper segment closer to remote CAN devices. The distance of the CMCs from the rest of the CAN-connected devices, and their use of high current to run the motors, present a higher risk of EMI in the copper-based CAN segments. By separating the CAN segments with Fobes and fiber optic cables this risk is mitigated.

The CAN-connected relay box by Blink Marine (Italy) enables relays to be opened and to be closed by means of CAN messages. This provides an audio annunciator capability that can provide key alarms to the X-57 pilot. These alarms are defined collaboratively with the test pilots, system designers, and operations team. The audio annunciator works by grounding specific inputs to the device, resulting in output in the form of an audio message. CAN messages from the ACL to the relay box energize relays, which completes the circuit to the annunciator, allowing the ACL to determine any alarm states and to alert the pilot both audibly (through the audio annunciator) and visually (through the D175 display). The audio annunciator that uses the relay box is a PRD60 accessory device developed by ▷

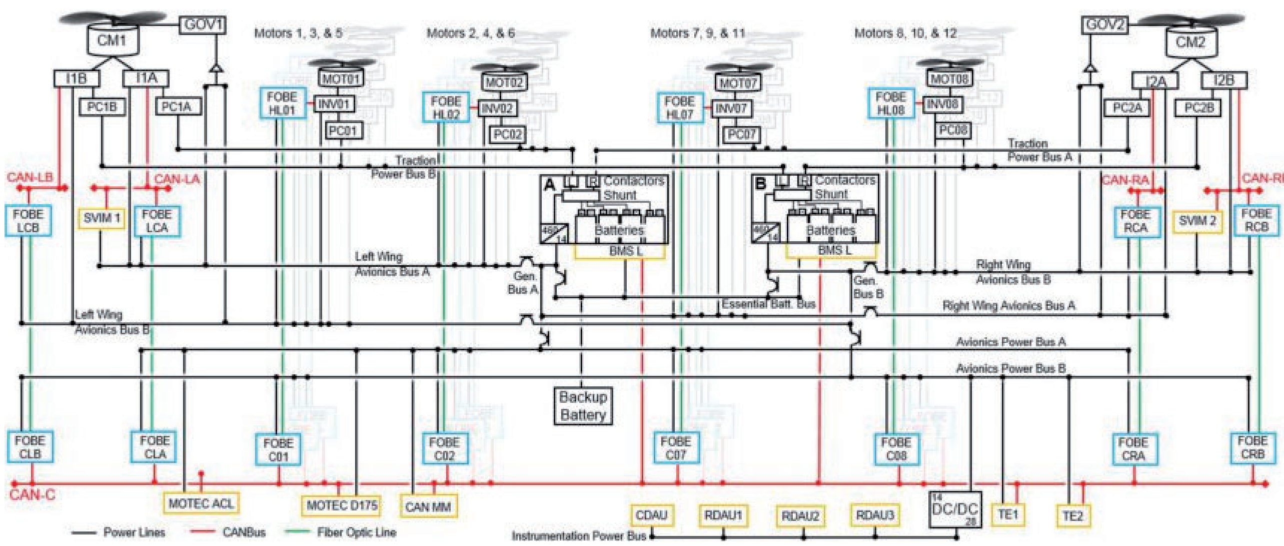

Figure 3: Block diagram of the X-57 command system network system, with commercial off-the-shelf (COTS) CAN segments (Source: NASA)

Figure 4: The ACL logger communicates via CAN with multiple SVIM input modules (Source: Motec)

PS Engineering (Lenoir City, TN). The device contains six pre-programmed messages and the ability to mute messages by acknowledging them with a simple push-button.

The X-57 instrumentation system contains a CAN network monitoring card that is linked to the command system. This card is used to only listen to the traffic on the CAN network and to record all of that traffic with a time tag. A subset of these messages is also transmitted to the ground station.

Risk mitigation

The X-57 CANopen command bus is considered a mission-critical system, but not a safety-critical system. This designation is possible because the pilot does not need to rely on the bus system for the safe operation of the X-57 flight demonstrator aircraft. All of the safety-related information provided by the CAN network is also independently measured and displayed on the right-hand instrument panel in the cockpit. The X-57 aircraft is also designed with an unpowered reversion mode, in which the pilot can safely control the aircraft and complete an unpowered, higher speed landing. This capability is facilitated by limiting flight to the area over Rogers' dry lakebed (Edwards, California), which provides ample landing options.

Although the command system itself is not safety-critical, the CMC and BMS, which are safety-critical devices, do interface with the CAN network. A bus failure for the X-57 flight demonstrator aircraft could result in a loss of communication to and from the mentioned safety-critical devices. Therefore, the BMS and CMC are designed to behave in a safe manner in case of bus failure. The BMS operates independently and only reports health and status to the network. It also reports operational status directly to the independent annunciator panel in the cockpit. The CMC, however, relies on command inputs received via CAN, so the CMC includes safety features to allow safe operation of the X-57 aircraft in spite of command bus interruption. If a command is lost from the throttle encoders, an internal CMC counter increments. During an initial count-up period, the last verified torque command is held and executed by the CMC. After a preset time, the CMC will execute a gradual ramp-down of the commanded torque to idle. These features enable continued operation for a short time after a bus failure. The preset timeout prevents an indefinite running of the motors in the case of ground testing, when the aircraft is being operated remotely. As a mission-critical system, additional measures are taken to reduce the risk of various command bus failures.

While the CAN physical layer makes the command bus resistant to EMI, steps are taken to further reduce the risk of the high-power systems introducing electric noise into the network. Mod II to the X-57 aircraft locates the CMC and motors in the same location as the original Tecnam engines. Mod III to the X-57 aircraft, however, requires the command bus to extend to that point. As such, the Fobes are used to incorporate the fiber optic cable segment between the fuselage and the CMC for both Mod II and Mod III. These Fobes operate in such a way that they are invisible to the devices on the CAN networks. The devices on either end of the fiber optic link behave no differently than if they were all connected by way of a copper cable.

To reduce the risk of throttle command failure, the throttle encoders used to measure the angle of the Tecnam throttle levers contain a redundant encoder. The encoder transmits the measurement from each encoder onto the CAN network. The device that read this information can then act on any discrepancies between the data reported by each encoder. A discrepancy between the two encoders is a case wherein which the CMC considers the incoming command as invalid and revert to the command bus failure mode, as described above. Further risk mitigation for the throttle encoders involves the physical device. The initial design to digitize the throttle position used a cable-pull encoder. This method was revised to use a rotary encoder that has a direct mechanical connection to the throttle levers to reduce the chance of the cable snagging.

The CAN physical layer provides redundancy for the motor commands. The data from each throttle encoder go to two CMCs on each side of the aircraft. To prevent a complete failure on one side in the case of a physical break of the CAN-based command bus, the physical tie-in of each CMC connected to the same motor is located on opposite ends of the network. Therefore, a break on one side of the CAN network ensures a physical path from the throttle encoders to at least one CMC on each side. ◀

hz

This article is based on the content of [1].

X-57 partners

- Baumer
- Blink Marine
- Electric Power Systems
- Joby Aviation
- Motec
- Tecnam
- Western Reserve Controls

References

[1] Sean Clarke, P.E., Matthew Redifer, Kurt Papathakis, Aamod Samuel (all NASA Armstrong Flight Research Center), and Trevor Foster (Empirical Systems Aerospace): X-57 power and command system design, NASA 2017.

Modularity