# Give. Sympathize. Control. Subverting the GZM48S Lawnmower via CAN*

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**Abstract**

I accessed the CAN (Controller Area Network) bus of the Greenworks Commercial Stand-On Mower (GZM48S). This CAN network was sniffed as various controls were manipulated. I analyzed the various CAN messages. I verified that, using my derived model of the CAN network, messages injected into the CAN bus had physical effects on the mower. I finally propose further steps necessary to reliably and smoothly control the mower from a ROS software stack.

## 1 Introduction

The GZM48S[6][7] is an electric, lithium-ion lawnmower designed for a standing human operator. Greenzie desires to autonomously drive this mower using their "Archer" ROS[15] software stack. Rather than attempt to mechanically manipulate the human controls, Dirty South Supercomputing was contracted to reverse engineer the mower's CAN bus, and determine whether the mower can be operated via CAN messages.

Sniffing the CAN bus revealed several dozen distinct CAN message IDs (CAN has no concept of source or destination addresses, but all message types have a unique 11- or 29-bit identifier). CAN IDs are not standardized across products, but by correlating the message types with various mower behaviors, it was possible to derive a consistent model of the message semantics. Various messages were composed by hand and injected into the CAN bus, with results including changes on the mower's LED, interruption of expected mower behaviors, and faulting the mower (requiring a power cycle).

It was not possible to initiate or maintain most motor effects via injected CAN messages, but this is explainable given the presence of CAN *message contention*[12]. ECUs (Electronic Control Units, the various nodes on the CAN network) typically broadcast their messages regularly, often dozens of time per second. When a message ID periodically sent by some ECU is injected by our stack, the ECU is likely to contradict that message within a short time (on the order of milliseconds), too quickly for motors to reflect the momentary engagement. It is not known whether this is the *sole* obstacle to controlling the motor with our stack—it is possible that further controls restrict our CAN messages from controlling the motor and blades. A plan for weapons-grade control is proposed, which I believe to be feasible.

## 2 Setup

The Greenworks Commercial GZM48S mower's rear electrical area, when opened, reveals a male DE-9. This interface seems wired according to §6.1 of the CiA 303-1[3] recommendation regarding the ISO 11898-2[1] CAN specification ("D-SUB 9-pin connector"). The PEAK System PCAN-USB[9] IPEH-002022[1] bridges a corresponding female DE-9 to a USB 2.0 Type A, employing an NXP SJA1000[14] controller and an NXP PCA82C251[13] transceiver. CAN buses are not guaranteed to be safe for hot-added devices; it is advised to connect the PCAN to the bus only while the mower is powered off[2].

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[1]This variant includes a TLP291 optocoupler.

[2]In practice, ensuring that GND is connected prior to $V_{cc}$ should suffice.

## 2.1 Host side

The PCAN was connected to a Lenovo T580 laptop running a custom 5.1.3 Linux kernel and Arch's version 2018.02.0-3 of the *can-utils*[11] tools[3]. It was recognized by the `peak_usb` kernel module, and verified as having the current firmware (version 8.4). `peak_usb` is a SocketCAN driver, and results in a network-style device e.g. `can0`. This device requires, at minimum, timing configuration. It was possible to sniff packets without registered errors using the `bitrate 125000` parameter to `ip`, indicating the CiA-recommended timing[17] for a 125kbit/s network[4]. At other rates (including 500 and 250kbit/s), we received only errors.

The following further options were applied to the interface:

- `restart-ms 1`: Renegotiate as quickly as possible if we enter the BUS-OFF error state.
- `one-shot off`: Retransmit on ACK failure.
- `berr-reporting on`: Enable error reporting IRQs.

We explicitly do *not* use `triple-sampling on`, `listen-only on`, nor `fd on`. See the "Questions" section regarding FD. A series of captures were acquired on-site the Saturdays of 2018-05-11 and 2018-05-18. The command used to generate the captures was:

```
candump -ta -a -l -r$((1024 * 1024 * 8)) -D -d -l can0,0:0,#FFFFFFFF
```

At least 500 packets were seen per second when the mower is powered on, rising as high as the 600s. These logs can be replayed using `canplayer` either onto a virtual CAN device (for analysis with e.g. `cansniffer`) or onto a physical CAN interface for injection. They are most easily viewed as ASCII text using `log2asc`. All three programs are distributed as part of *can-utils*. While the dump was running, interface state and statistics were monitored using:

```
watch -n2 ip -details -s l show can0
```

It is important to watch both RX and TX errors, as well as the CAN controller's error state[10]. A CAN controller can be in one of three error states:

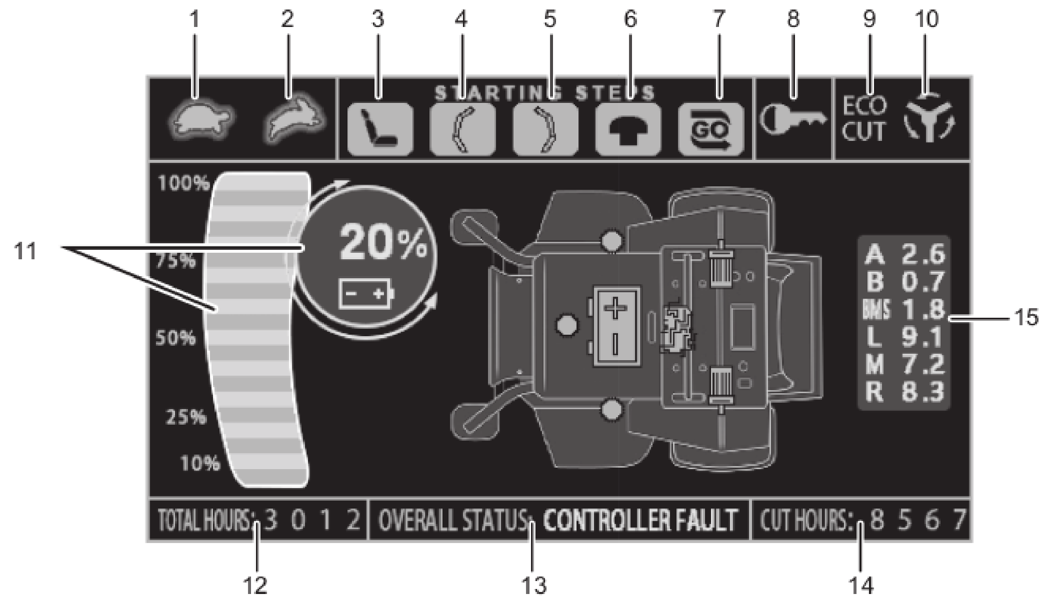
- ERROR-ACTIVE: The controller can transmit normally.
- ERROR-PASSIVE: The controller must wait longer to transmit, and may not send active error frames.
- BUS-OFF: A conforming device must not transmit until renegotiated.

While the `restart-ms 1` option will result in quick renegotiation, it is undesirable to enter this state, and makes transmission impossible using most devices. Note that these error-containment mechanisms can themselves be exploited as a DoS attack[5].

## 2.2 Mower side

With regards to the mower, we are most interested in the left and right steering control lever (each can be independently placed in forward, backward, neutral, or the parked default), and the pressure sensor underneath the operator's stand. Without effort, both levers will spontaneously return to the disabled state, and the platform will return to its original level. If any of these three inputs are not engaged, the unmodified mower will not move. Of further interest are the drive speed switch, the blade speed switch, and the blade engagement button. All three retain whatever state they're placed in, and it is thus less critical to manage them via the CAN bus.

[3] v2018.02.0 was current in both Arch and Debian Unstable at the time, though commits have been made since then.
[4] 8$\mu$s nominal bit time $t_B$, 16 quanta per bit, 625ns time quantum $t_q$, samplepoint at $14t_q$ (7$\mu$s).




**Konw the digital display**

| No. | Icon | Meaning |
|---|---|---|
| 1 | | low drive speed |
| 2 | | high drive speed |
| 3 | | seat switch |
| 4 | | left control lever |
| 5 | | right control lever |
| 6 | | PTO switch |
| 7 | | the whole machine is OK |
| 8 | | need to restart |
| 9 | ECO CUT | low blades speed |
| 10 | | blade working |
| 11 | | battery remaining capacity |
| 12 | Total hours | total working hours |
| 13 | Overall status | controller fault/ battery fault/ motor fault |
| 14 | Cutting hours | cutting hours |
| 15 | L | left blade motor fault code |
| | A | master controller fault code |
| | BMS | battery fault code |
| | R | right blade motor fault code |
| | B | slave controller fault code |
| | M | middle blade motor fault code |

**Figure 1:** GZM48S display[6]. "Konw" *sic.*

It is possible to send the controller into a fault state (indicated by illumination of the key icon (8) above) by injecting CAN frames. If this occurs, the mower must be power cycled using the key. It has not been determined whether this condition can be worked around via CAN bus. There are several less critical faults, unaccompanied by the key icon. Powering the mower on with the blade button engaged will boot into a controller fault, as will disengaging the pressure sensor while the mower is operating. The leftmost three icons of the “starting steps” (3–5 above) must be lit, or the mower will not move. The fourth icon (6) must be lit, or engaging the blades button (“PTO switch”) will not start the blades.

The Owner’s Manual rewards a close inspection. The diagram and accompanying text suggest presence of both a “master” and “slave” controller. The terms could suggest a failover protocol at work. CAN itself is a multi-master protocol, but the CiA’s CANopen[4] higher-layer protocol does have a concept of masters and slaves. Note that it is implied that the master speaks to the BMS (Battery Management System) and deck[5] motor controllers, but that both the master and slave speak to the HPD. “KSI” pretty clearly means “Key Switch Input”, but what’s an HPD? Human Protection Device? Searching for this term in a CAN/industrial context pulls on a thread which unravels to suggest that our two drive controllers are Curtis 1234[8] AC Induction Motor Controllers, eventually confirmed via visual inspection[6]. The 1234 speaks CANopen, and can be configured as a CANopen master or slave. Later use of the term “CAN NMT” would seem to refer to CANopen’s Network Management Protocol, of which there is no concept in raw CAN. Indeed, we find CANopen NMTs in the packet captures. Realizing this was a critical step in making sense of some of the more complex CAN frames. Always study the documentation!

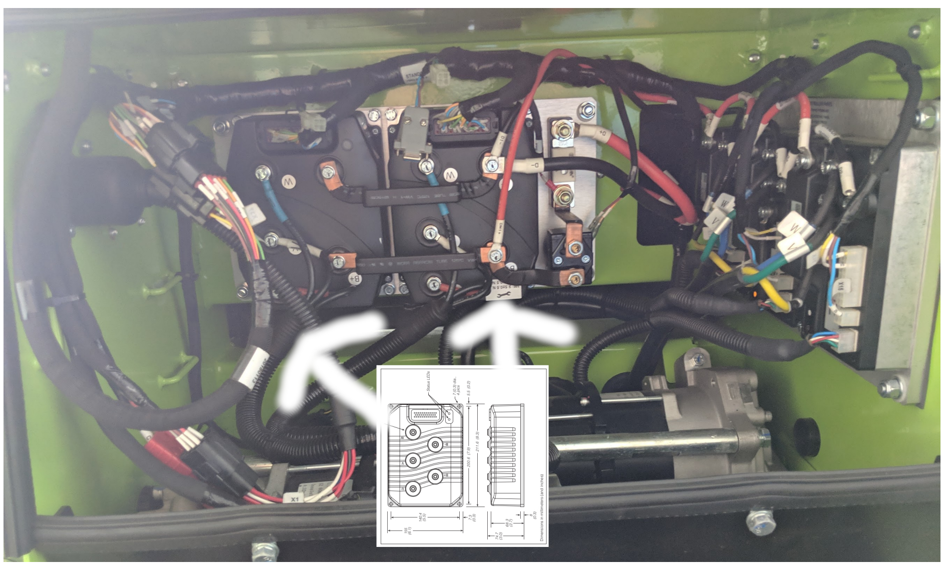


**Figure 2:** GZM48S electrics bay, and diagram of Curtis 1234. It’s a match!

## 3 Data and Interpretation

As described above, traffic was captured using `candump`. It was then analyzed using `cansniffer`, Savvy-CAN[16], and bespoke tools.

### 3.1 CAN frames and semantics

CAN is a minimalist link protocol. An 11-bit ID is mandatory, though modern CAN networks support an extended 29-bit ID. This ID applies to a message *type*; there is no concept of addressing in CAN. Logical 0 is *dominant* over the *recessive* logical 1—if any node transmits 0 during a bit, all nodes will see 0. Nodes must listen to the bus while transmitting, and if they read a 0 while sending 1, must consider it a TX error. This does not apply while transmitting the ID, which is near the head of the frame. In this case, the node ought simply stop transmitting, and consider the bus arbitrated away. Lower IDs thus have built-in priority over higher ones in a compliant network. Each frame carries up to 8 bytes of payload. As noted earlier, there are no “well-known” CAN IDs in the sense of e.g. TCP ports.

[5]“Deck” and “blades” are used in a weird metonymy throughout the manual.

[6]The mysterious HPD means “high pedal disable”, copied word-for-word from a Curtis manual.

There is an element of support for single-message request-response in CAN, but the vast majority of traffic tends to be unilateral broadcasting[7]. More generally relevant is acknowledgement: towards the end of the frame is an "ACK slot". The transmitter must transmit 1 for this bit, while listeners ought transmit 0. If the transmitter does not read a 0, the message is unacknowledged, and should be retransmitted. It is not generally possible to determine how many nodes on the network ACKed the message, only that at least one did. It is finally important to know that, upon encountering an error while in the ERROR-ACTIVE state, a node transmits the Active Error Frame, which will collide with any ongoing message (prompting a cascade of secondary error frames from other ERROR-ACTIVE nodes)[8].

## 3.2 The GZM48S CAN bus

The following 46 11-bit IDs were seen (not all were seen in all logs):

| ID | Len | ID | Len | ID | Len | ID | Len |
|---|---|---|---|---|---|---|---|
| 1A6 | 8 | 1A8 | 8 | 1A9 | 8 | 1AA | 8 |
| 1AC | 8 | 224 | 8 | 225 | 8 | 226 | 8 |
| 228 | 8 | 229 | 8 | 22A | 8 | 22E | 8 |
| 2A6 | 8 | 2A8 | 4 | 2A9 | 4 | 2AA | 4 |
| 2AC | 8 | 301 | 8 | 302 | 8 | 303 | 8 |
| 304 | 8 | 305 | 8 | 306 | 8 | 307 | 8 |
| 308 | 8 | 320 | 8 | 321 | 8 | 326 | 8 |
| 350 | 8 | 351 | 8 | 352 | 8 | 353 | 8 |
| 354 | 8 | 355 | 8 | 3AC | 8 | 5A8 | 8 |
| 5A9 | 8 | 5AA | 8 | 628 | 8 | 629 | 8 |
| 62A | 8 | 726 | 1 | 727 | 1 | 728 | 1 |
| 729 | 1 | 72A | 1 | | | | |

Already some patterns can be perceived. The same lower eight bits are seen in many IDs—A8, A9, and AA show up together, as do 28, 29, and 2A. All frames appear to have 8 bytes except for those prefixed with 7, which have 1 byte, and some prefixed with 2, which have 4 bytes. Remember that higher IDs have lower priority. Given that the lowest priority messages have only a single byte, perhaps these are low-information heartbeats? Inspecting the 7xx frames shows that they are all the same value (0x05), except upon boot. On boot, they all show 0x7F. Together with a lack of any plausible prompting (why would larger messages having higher priority be used to request such short ones?), this could indeed possibly be either two request-response heartbeats, or four unilateral ones.

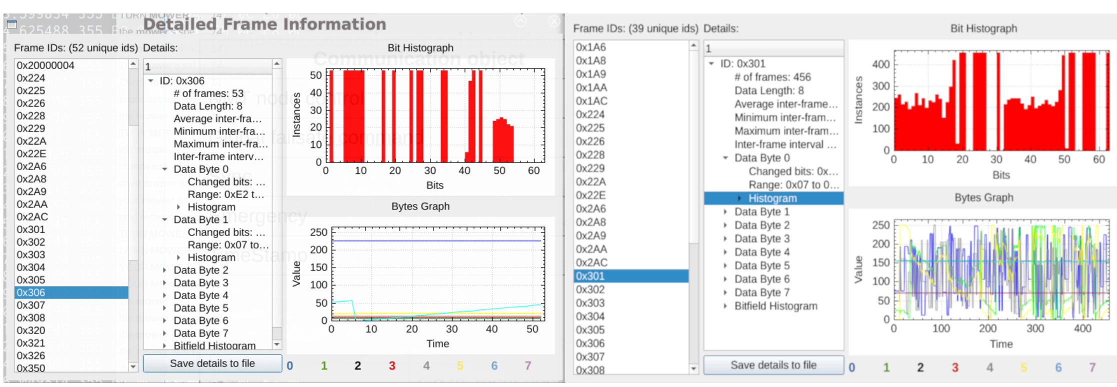



**Figure 3:** Frame data analysis of two IDs using SavvyCAN.
What's going on in the left is pretty obvious. The right, not so much.

[7]A request is a "Remote Frame". A broadcast—unilateral or requested—is a "Data Frame".

[8]The active error frame is 6 dominant bits followed by 8 recessive bits. Due to the use of non-return-to-zero line coding with a length of 5, six clocks of 0 are guaranteed to provoke the "bit stuffing" error on compliant, operating nodes.

In the case of 0x306, we see a lower-order byte rising in exact, visibly-recognizable synchronization with time. When it reaches its maximum, it resets, and a higher-order byte increases, yielding a fractal sawtooth. This can be nothing but a monotonically increasing counter, and its wide domain suggests it to be a clock. We verify that it is persistent across runs, and identify it as the source of "total hours".

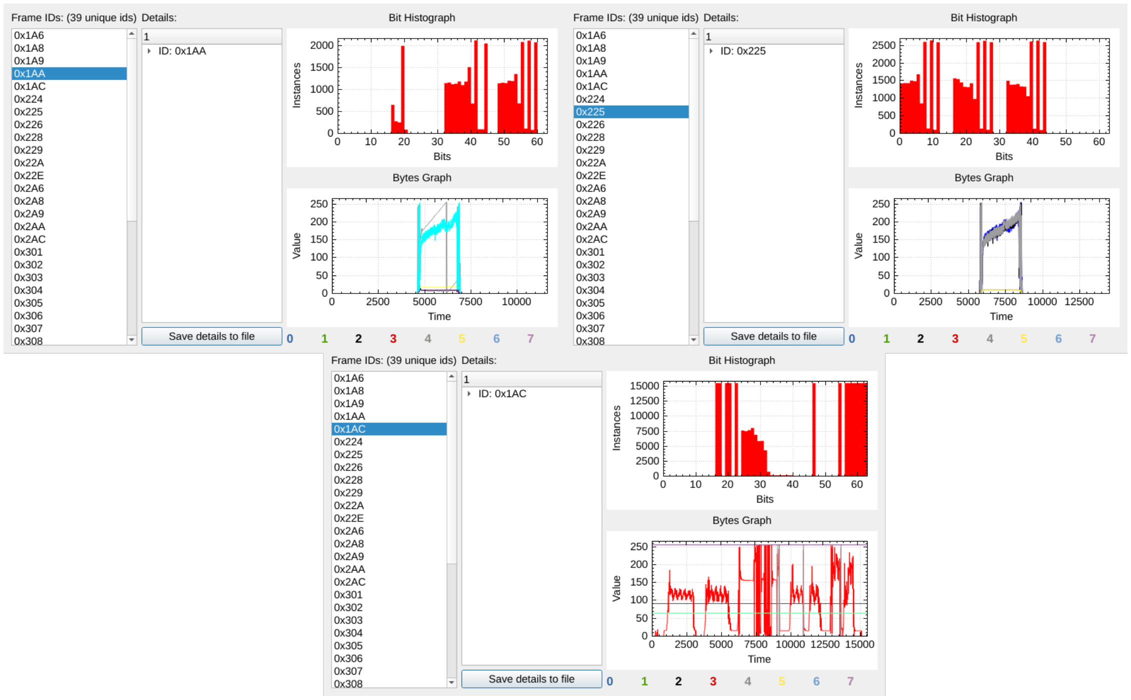



**Figure 4:** Three IDs. Two are obviously correlated.
The bottom seems possibly to subsume the two on top, along with other data.

During the first day's sniffing, the battery display indicated a 91% charge. The second day showed 90%. These correspond to 0x5B and 0x5A, respectively. In every frame having ID 224, the first byte is…0x5B on the first day, and 0x5A on the second. Let's call it the human-readable battery level. This suggests that 224 is either a message to the display, or a sensor message from the BMS. It seems unlikely that the physical sensor would report a human-readable value. It is determined that only the penultimate byte of 224 seems otherwise to change, and it in very sharp, long-held changes among a few values, usually in single-bit changes (e.g. 0xC to 0x4). This might plausibly be a bitmask for the lights of the display. Could the other six bytes correspond to the six error values? It's all reasonable, but by no means guaranteed.

The two analyses above involved sorting by ID and inspecting change among the bytes of that ID's data frames. Stepping back, we sort by time, and plot all the IDs, coloring them according to payload value:

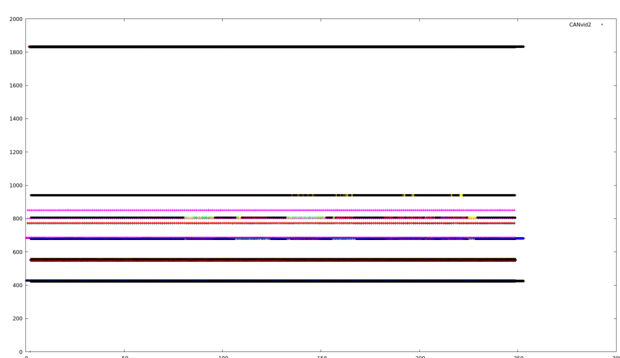


**Figure 5:** (Decimal) IDs over time, colored by payload.

How many distinct nodes are responsible for these messages? We noted earlier that the same lower 8 bits show up a few places. Assuming IDs beginning with 1 to be inputs (hence low priority), I hoped to find a correlation between e.g. 1A8, 1A9, 1AA and 2A8, 2A9, and 2AA. Alas, there is none—but there most definitely exists one between 1A8, 1A9, 1AA and 228, 229, 22A! This difference of 0x80 is repeated in 5A8, 5A9, 5AA and 628, 629, and 6AA...and in an ephiphany, we reach a new conjecture: the lower **seven** bits could be node IDs, in which case 1A8, 228, 2A8, 5A8, 628, and 728 are all a single node, 0x28. This unification would account for essentially every ID save the 3xx series in just ten nodes. Inspecting the logs, we do indeed see tight association between e.g. 1A6 and 226, and 2A6 and 326. This interpretation grows more and more compelling.

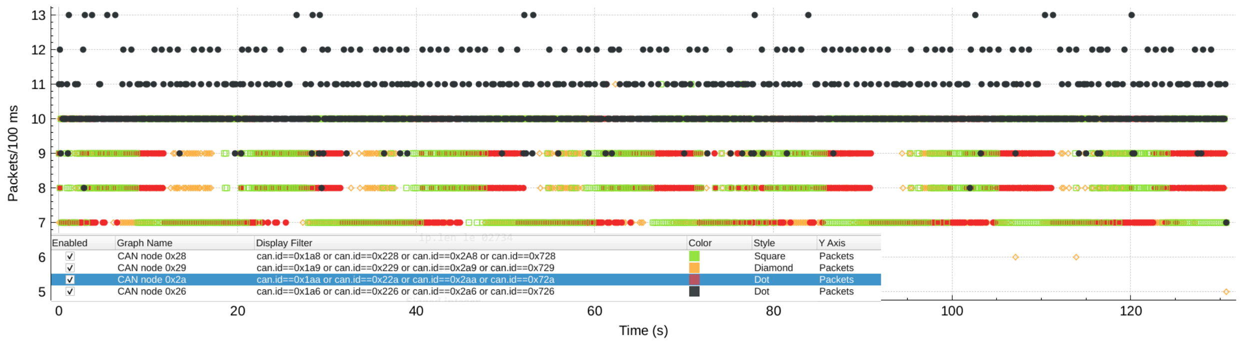



**Figure 6:** Wireshark I/O plot of four conjectured nodes.

At this point, we have enough information to consult known higher-level protocols. As mentioned earlier, the term "NMT" is used once in the manual, copied from the Curtis 1234 error descriptions. This could be CANopen (which is indeed supported by the Curtis unit), with its Predefined Connection Set:

| Message | Function code | CAN-ID base | COB-ID parameter index |
|---|---|---|---|
| NMT | 0000 | 000 | Not configurable |
| SYNC | 0001 | 080 | 1005 |
| EMCY | 0001 | 081–0FF | 1014 |
| TIME | 0010 | 100 | 1012 |
| $TPDO_1$ | 0011 | 181–1FF | 1800 |
| $RPDO_1$ | 0100 | 201–27F | 1400 |
| $TPDO_2$ | 0101 | 281–2FF | 1801 |
| $RPDO_2$ | 0110 | 301–37F | 1401 |
| $TPDO_3$ | 0111 | 381–3FF | 1802 |
| $RPDO_3$ | 1000 | 401–47F | 1402 |
| $TPDO_4$ | 1001 | 481–4FF | 1803 |
| $RPDO_4$ | 1010 | 501–57F | 1403 |
| TSDO | 1011 | 581–5FF | Not configurable |
| RSDO | 1100 | 601–57F | Not configurable |
| Heartbeat | 1110 | 701–77F | Not configurable |

It seems safe to proceed under the assumption that CANopen is in play. We replay the `candump` log over a virtual CAN interface[9], and capture it in Wireshark[18], applying its CANopen secondary decoder. The various frames all decode into reasonable CANopen, and a node table emerges:

| Node | TPDO1 | RPDO1 | TPDO2 | RPDO2 | TPDO3 | NMT | TSDO | RSDO |
|---|---|---|---|---|---|---|---|---|
| 0x26 | 1A6 | 226 | 2A6 | 326 | | 726 | | |
| 0x27 | | | | | | 727 | | |
| 0x28 | 1A8 | 228 | 2A8 | | | 728 | 5A8 | 628 |
| 0x29 | 1A9 | 229 | 2A9 | | | 729 | 5A9 | 629 |
| 0x2A | 1AA | 22A | 2AA | | | 72A | 5AA | 62A |

[9] Use the Linux `vcan` module.

TPDOs 0x2A8, 0x2A9, and 0x2A are responsible for the 4-byte messages. All other messages, save the single-byte 0x7xx-series heartbeats, are 8 bytes. It seems reasonable to assume that these three nodes—0x28, 0x29, and 0x2A—are a logical group, and indeed they are almost certainly the three blade controllers (see the right side of Figure 2). Their activity takes a distinctly different form when the blades are engaged, and the SDO messages to and from these nodes are (sometimes, but only) sent immediately prior to blades turning on. Analysis of the NMT state machine and the 7xx messages confirms this, and further implies 0x26 and 0x27 to be a group. It's almost certain that these are the Curtis drive controllers, and examining the changes in TPDOs 0x1A6 and 0x2A6 confirms a strong correlation with mower movement.

The changes in 0x224, as noted earlier, seem to cover the gamut of state changes, and can be put on an isomorphism with display changes. The first two bytes are a human readable battery level. The seventh byte is a bitmask corresponding to the top row's icons (save the key icon, and with a sole bit to choose between the mutually exclusive low and high speed glyphs). The other six bytes probably carry the six error codes. The two hour counts correspond to four bytes of the clock signal at node 0x06.

If the motor controllers are to be driven through CAN in their current configuration, I suspect that it would be via RPDO 226 and 326, but I cannot isolate a control signal on these IDs. Nor can I correlate any other signal to the drive levers. Examining its manual, the Curtis 1234 does not appear, by default, to use CAN bus as an input, but rather the various throttle and brake pot inputs. CAN is instead being used to report motor state, including level and temperature. The Curtis 1234 supports uploading firmware written in Vehicle Control Language, and it is probable that CAN could be used as a control input with a custom firmware. It would likely be easier, however, to drive the input lines from the Archer system. It *does* seem likely that the blade controllers are set up for driving with CAN, due to the exchange of SDO messages. As noted above, however, this does not always happen upon blade engagement.

# 4 Replay experiments

I injected CAN frames via two different strategies: bulk replay of recorded traffic, and surgical injection of packets constructed according to the analysis above.

Traffic sniffed while standing on the pressure sensor, replayed while not standing on the sensor, did indeed cause the display to illuminate the stand light. The light flickered, presumably due to contradictory messages being interleaved with the replayed messages. At no time did the mower begin moving, despite the traffic being sniffed while moving. This is almost certainly due to the KSI system being hard-wired to the motor controllers (it has distinct wired inputs), and said controllers synthesizing these values on 224 outputs. I then dropped all but the 224 messages from this traffic, and repeated the experiment. The same results were seen.

Traffic sniffed while *not* standing on the pressure sensor was then replayed while standing on the mower with the levers in park, leading to the sensor light flickering. This was again due to RPDO 224. I began driving the mower forward, and played this traffic back once more. The light flickered, and the mower stuttered, but no recoverable controller fault (as occurs when one jumps off the stand while moving) was seen. This latter lends credence to the idea that the display is controlled by CAN, but the motor controls are not. The stuttering of the mower, however, would seem to suggest otherwise. It is possible that we were momentarily stopping the motor, but that ought have led to a safety fault; I instead believe that dumping so much traffic onto the CAN bus (the messages were injected in a tight loop) simply upset the controllers. Certainly I was unable to cause a sedentary mower to move, however stutteringly.

Sending enough traffic, of any kind, eventually led to non-recoverable controller faults, likely due to drowning out of important messages (including heartbeats).

# 5 Towards control

The following facts are now known:

- CAN frames can be sniffed from the DE-9 port, and these CAN frames can be consistently correlated with mower operation.

- CAN frames injected via the DE-9 port can result in changes to the mower's display, including turning on lights indicating control engagement. Of the four lights necessary to trigger the mower's "GO" light, all four (stand pressure, left control, right control, blades enabled) can be illuminated by CAN frame injection.
- CAN frames injected via the DE-9 port can result in degraded mower, functionality, including disabling blades and retarding movement.
- CAN frames injected via the DE-9 port can fault the mower, requiring a restart. A restart requires at least 5 seconds.

No concrete mapping of CAN traffic to desired mower behavior has been found. That doesn't mean that none exists. Aside from simply overlooking a signal, the following are all possible:

- Contradictory messages—message contention— could be invalidating our constructed controls. This would mean I've misidentified an input as an output, and that the Curtis controllers have been reprogrammed for CAN control, in a way that would seem to require custom VCL. If this is true, working around the issue would require either disconnecting the true CAN input (electrically or via DoS), timing our messages to arrive precisely after that input (plus luck—it's in no way certain that this would result in deired behavior), or invalidating each broadcasted input.
- My injected messages are being filtered from the controllers (but not from the display, which we can affect).
- CAN controls are checked against the electromechanical inputs, and ignored if they're clearly incompatible (very likely for e.g. safety systems).

If my conjectured control messages are indeed correct (I do not think that they are; I believe them to be outputs, not inputs), and their failure is due to contention, it ought be possible to disconnect the conflicting controls, and see them work. I do not expect this line to succeed after reading the Curtis manuals and running my tests.

I see no means for our messages to be filtered from the drive controllers, but not filtered from the display. This would seem to require two distinct CAN buses, with a filtering bridge in the middle. I see no indication of such a device, and again, this is predicated on the controls being correct in the first place. If they are correct, but being checked against electomechanical inputs, it seems unlikely that the supposed CAN controls would work in the absence of said inputs, meaning they'd need be controlled in any case.

I thus recommend that efforts to drive the GZM48S focus on using the Curtis controllers' non-CAN inputs. These interfaces are fully documented, and known to work. If driven by the Archer stack, there exist no other controls to compete with our operation. A less appealing option is to write new VCL for the controllers, and upload it using a 1311 programmer, an operation too far removed from my skill set for meaningful comment.

On the plus side, should such control be put into place, the sensor signals emitted in the CAN network now seem well understood, and can be used by our system.

# 6 Questions

- The PCAN-USB manual claims that soldering is required to effect the necessary 120Ω termination for Hi-Speed CAN (ISO 11898-2), or a PCAN-TJA1054 bus converter for Lo-Speed CAN (ISO 11898-3)[2]. Neither of these options were used. The PCAN appeared to work fine with the network at 125kbit/s. Is this correct, or are we missing something?
- The created network device's MTU is 16, not the 72 expected from FD-capable CAN. Are we possibly missing CAN FD messages? It might be best to test with https://www.peak-system.com/PCAN-View.242.0.html.
- I did not attempt to scan or otherwise interrogate the ECUs using e.g. the ODB-II diagnostic protocol. Might there be things waiting, listening?

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