ACT: Automated CPS Testing for Open-Source Robotic Platforms

A Case Study with Lingua Franca & LF Embedded Systems Labs

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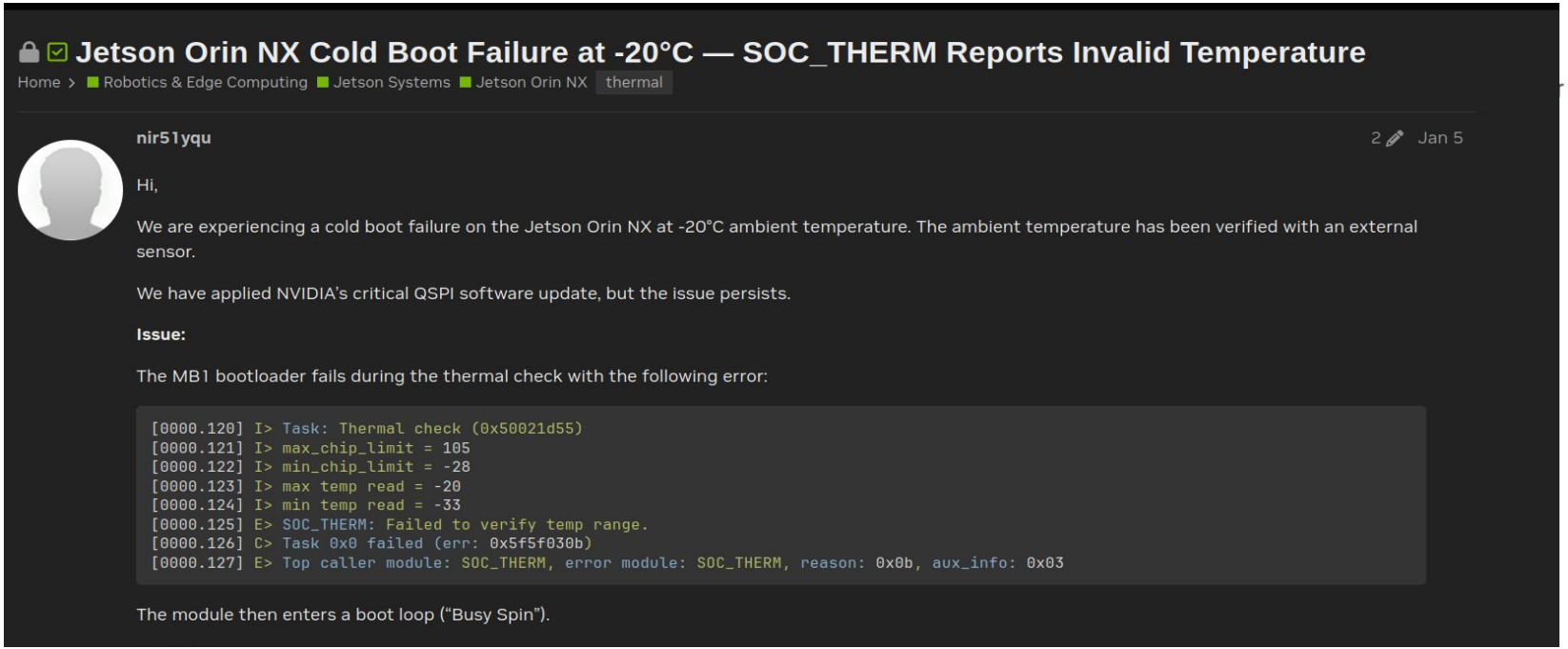
ARKANSAS STATE UNIVERSITY

Motivation

- Case 1: Thermal sensor of a device causing error during the booting process



Jetson Orin NX Cold Boot Failure at -20°C — SOC_THERM Reports Invalid Temperature

Home › Robotics & Edge Computing ■ Jetson Systems ■ Jetson Orin NX thermal

nir51yqu 2 Jan 5

Hi,

We are experiencing a cold boot failure on the Jetson Orin NX at -20°C ambient temperature. The ambient temperature has been verified with an external sensor.

We have applied NVIDIA's critical QSPI software update, but the issue persists.

Issue:

The MB1 bootloader fails during the thermal check with the following error:

```
[0000.120] I> Task: Thermal check (0x50021d55)
[0000.121] I> max_chip_limit = 105
[0000.122] I> min_chip_limit = -28
[0000.123] I> max temp read = -20
[0000.124] I> min temp read = -33
[0000.125] E> SOC_THERM: Failed to verify temp range.
[0000.126] C> Task 0x0 failed (err: 0x5f5f030b)
[0000.127] E> Top caller module: SOC_THERM, error module: SOC_THERM, reason: 0x0b, aux_info: 0x03
```

The module then enters a boot loop ("Busy Spin").

https://forums.developer.nvidia.com/t/jetson-orin-nx-cold-boot-failure-at-20-c-soc-therm-reports-invalid-temperature/356467

Motivation

- Case 2: Malfunctioning sensors and systems have caused serious accidents.

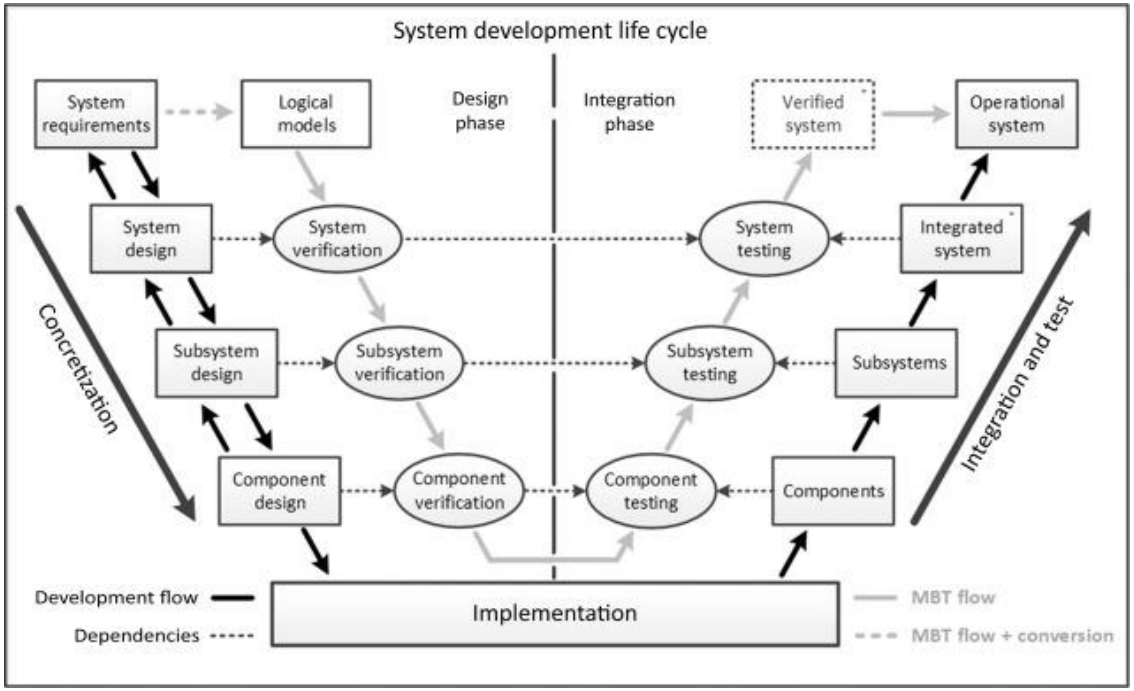
TRANSPORTATION

Boeing and Ethiopian investigators confirm a faulty sensor was triggered on the 737 Max shortly before it crashed

By **Benjamin Zhang**

https://www.businessinsider.com/boeing-ethiopian-investigators-confirm-bad-sensor-triggered-faulty-software-before-crash-2019-4

Motivation



- The System/Software Development Life Cycle (SDLC) includes many phases of testing for each verify a stage of the development before moving forward.
- Detecting bugs during each stage of testing has increasing difficulty and cost as the system nears the operational stage.

https://www.sciencedirect.com/science/chapter/edited-volume/pii/B9780128038017000195

Motivation - Embedded Systems Labs

Embedded Systems Labs

Institutions Using the Labs

The embedded systems labs with Lingua Franca have been used by various courses at institutions around the world, including the following (listed alphabetically):

- **Arizona State University, United States** — *CSE 522: Real-Time Embedded Systems*
- **Southern Illinois University, United States** — *ECE 424/514: Design of Embedded Systems*
- **University of California, Berkeley, United States** — *EECS 149/249A: Introduction to Embedded and Cyber Physical Systems*
- **University of Manouba, Tunisia** — *ESDV.5.4: Cyber-Physical Systems, ESEP.5.3: Cyber-Physical Systems*
- **University of Maryland, United States** — *ENEB452: Advanced Software for Connected Embedded Systems*
- **University of Michigan-Dearborn, United States** — *ME 472: Principles and Applications of Mechatronic Systems, ECE 566 / ME 565: Mechatronics*

If your institution is using the embedded systems labs but is not listed here, please email Hokeun Kim (hokeun@asu.edu) with your course information, or submit a pull request to add your course information.

https://www.lf-lang.org/embedded-lab

https://www.lf-lang.org

Motivation - Embedded Systems Labs

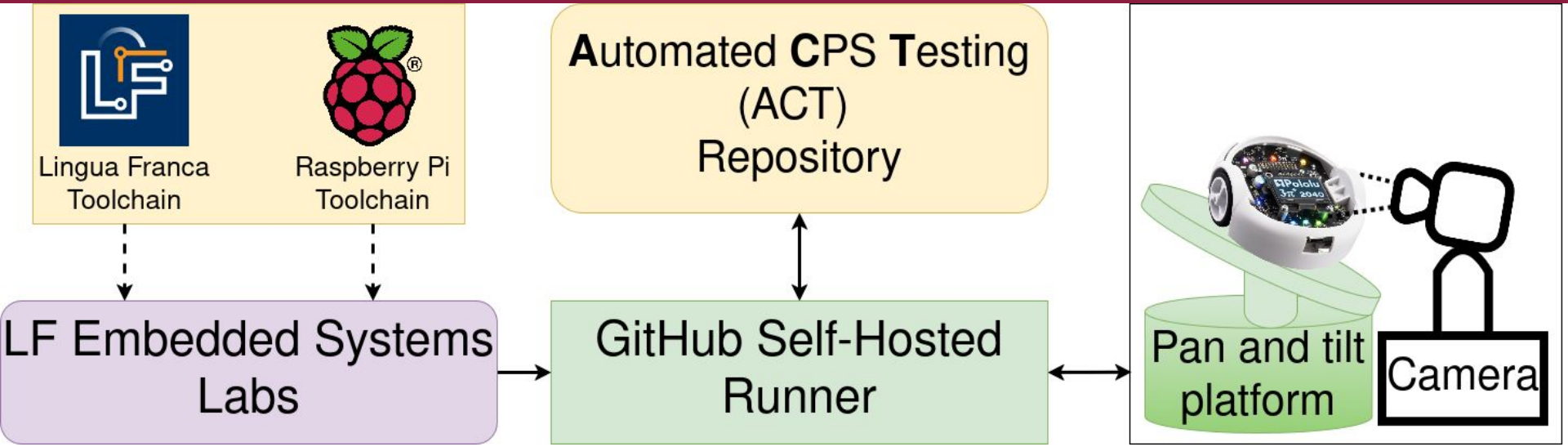
- **Students and TAs encountered issues with the build and toolchain setup.**

The updated `pico-sdk` version (2.2.0) required `picotool` (2.1.1), and the nix package manager was not fetching the new `picotool` version. This ended up to download the new `picotool` everytime we are doing `lfc`.

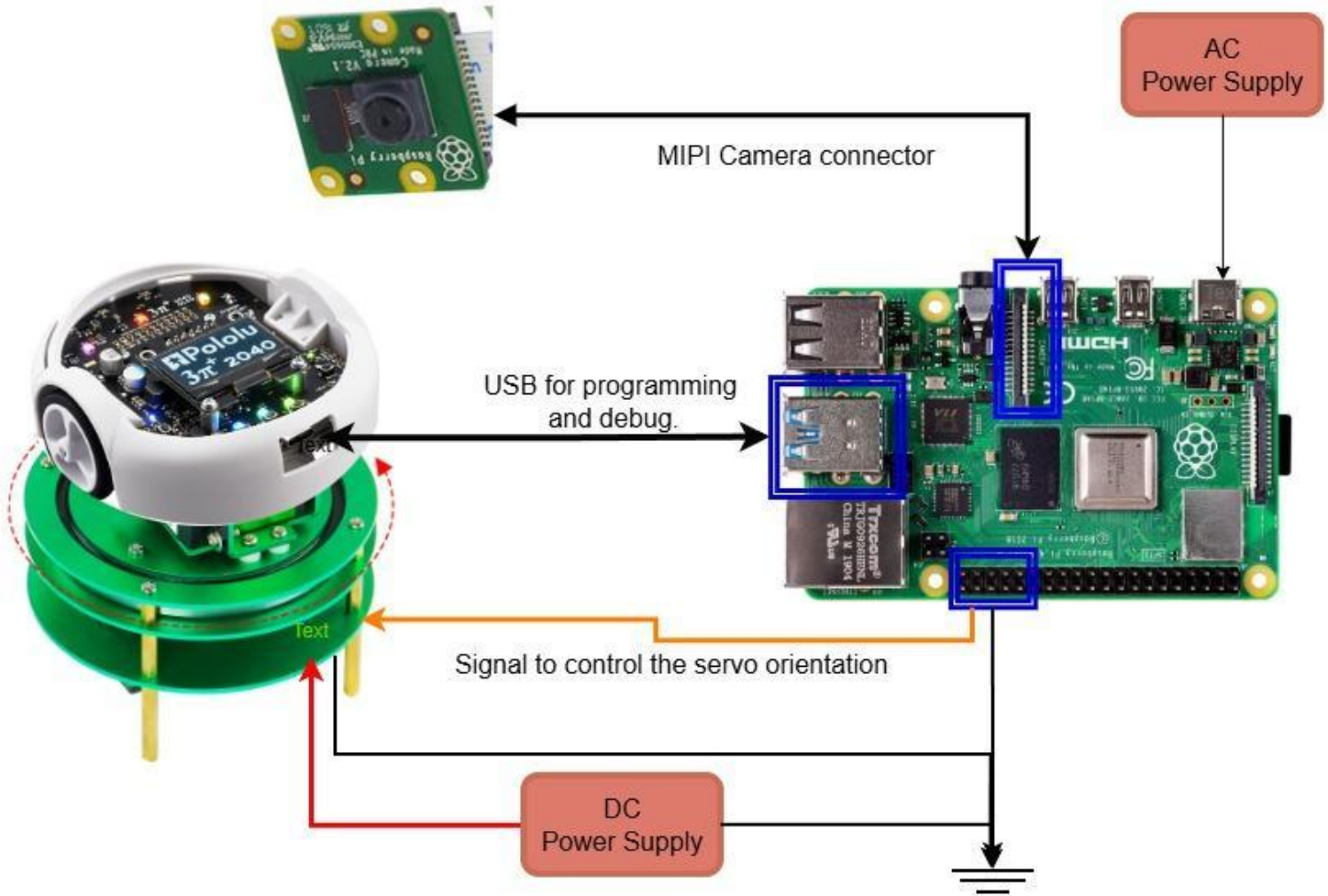
```
CMake Warning at /Users/dkim314/project/temp/pico-sdk/tools/Findpicotool.cmake:30 (message):
  No installed picotool with version 2.1.1 found - building from source

  It is recommended to build and install picotool separately, or to set
  PICOTOOL_FETCH_FROM_GIT_PATH to a common directory for all your SDK
  projects
Call Stack (most recent call first):
  /Users/dkim314/project/temp/pico-sdk/tools/CMakeLists.txt:168 (find_package)
  /Users/dkim314/project/temp/pico-sdk/tools/CMakeLists.txt:688 (pico_init_picotool)
  /Users/dkim314/project/temp/pico-sdk/src/cmake/on_device.cmake:81 (picotool_postprocess_binary)
  CMakeLists.txt:66 (pico_add_extra_outputs)


Downloading Picotool
```

This PR updates `nixpkgs` to version 25.05 in `flake.nix`, and will fetch the new picotool version. Thanks to @the-systematic-chaos

Proposed Setup - Block Diagram



https://www.lf-lang.org/ https://www.raspberrypi.com/ https://www.pololu.com/product/5001



Test cases

- **LED**

  LED serves as a representation of status indicators on robots or CPS.

- **Motors**

  Motors are actuators which allow motion on many robots.

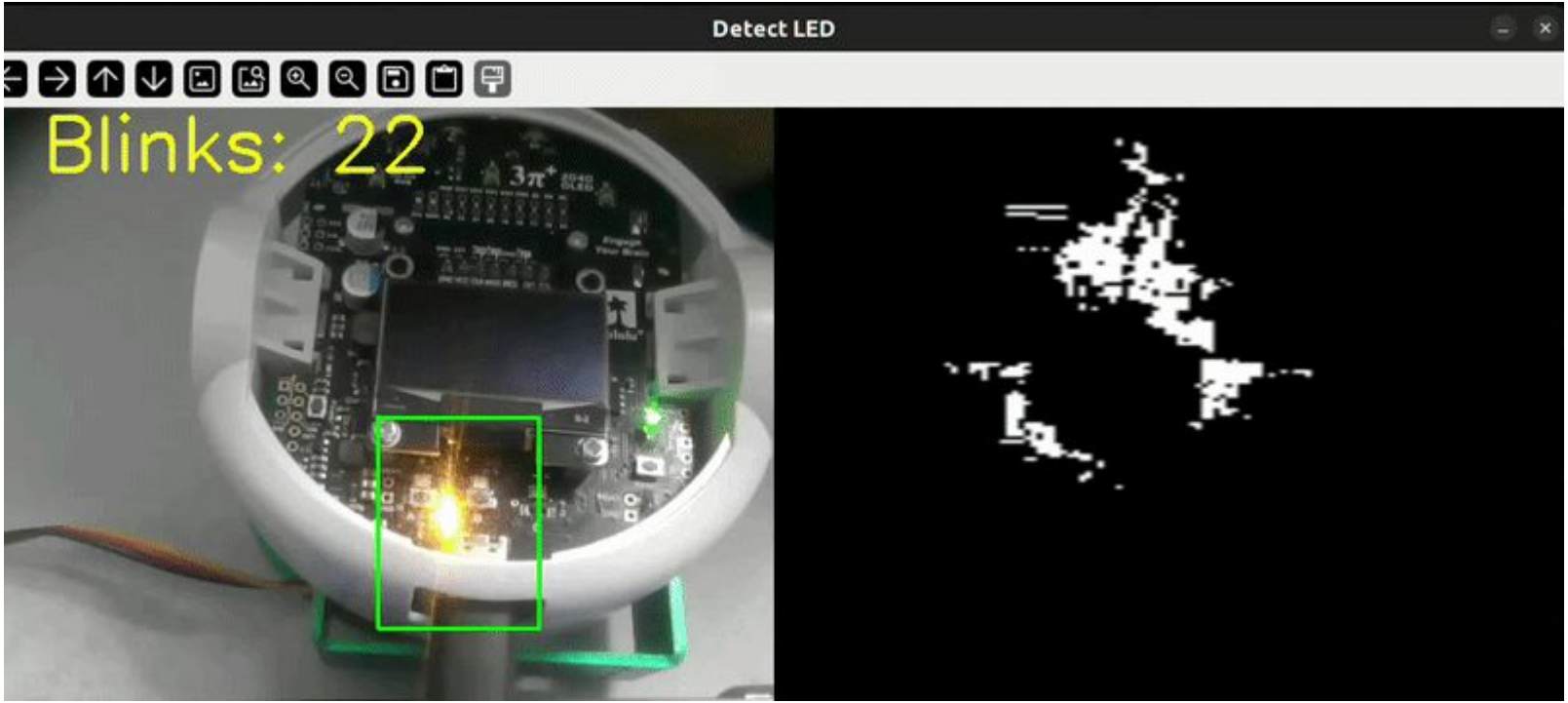
- **IMU and Display**

  IMU is used for navigation since there are no cameras on this robot.

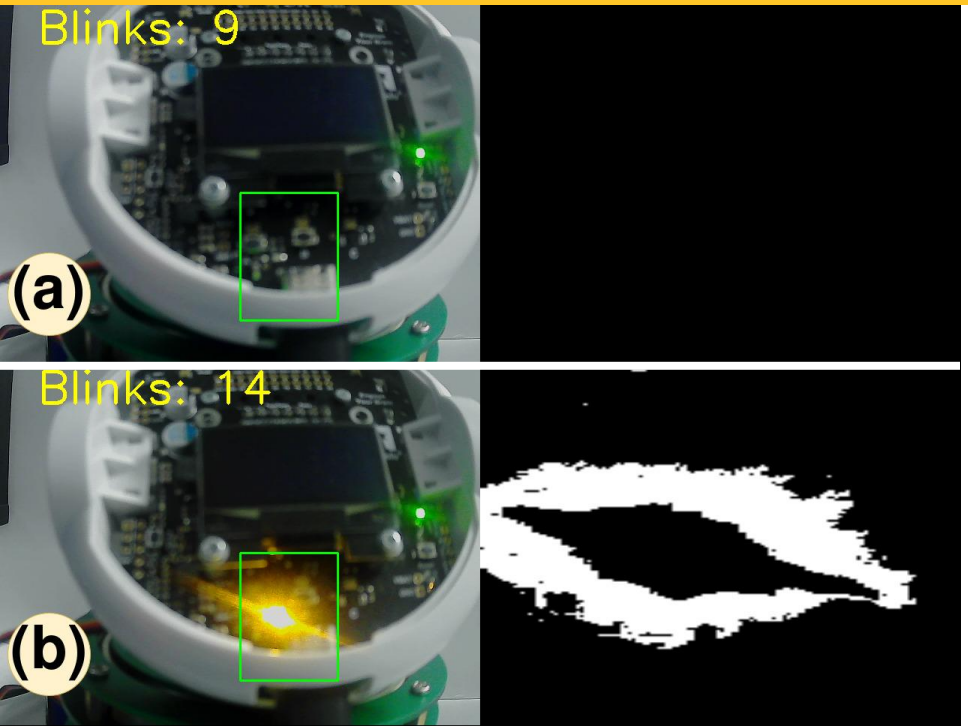
- **Bump and display**

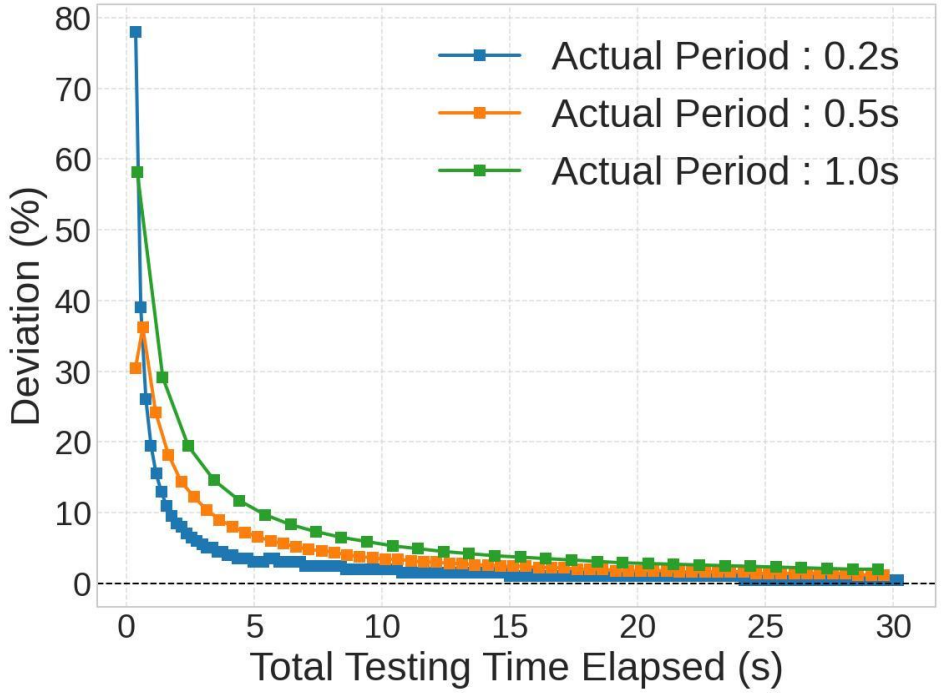
  The reflectance sensors are also used for navigation.

Test Case - LED



Test Case - LED

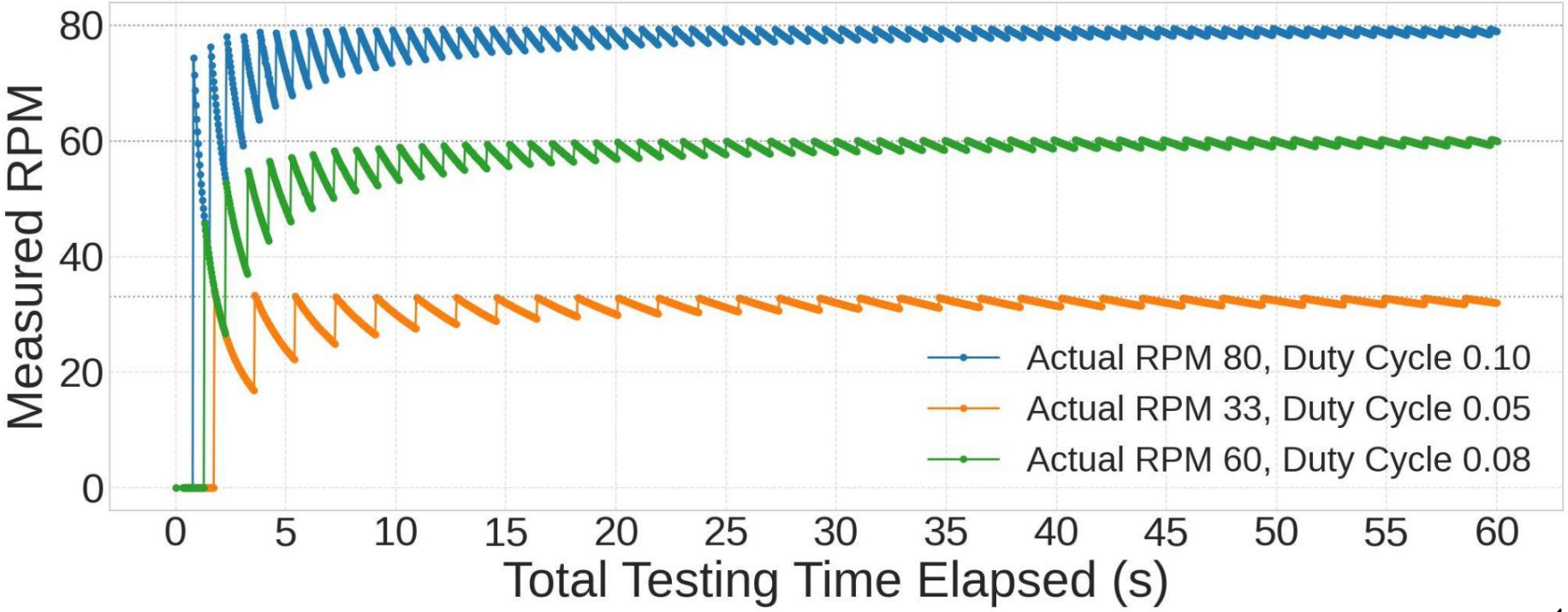




Test Case - Motors

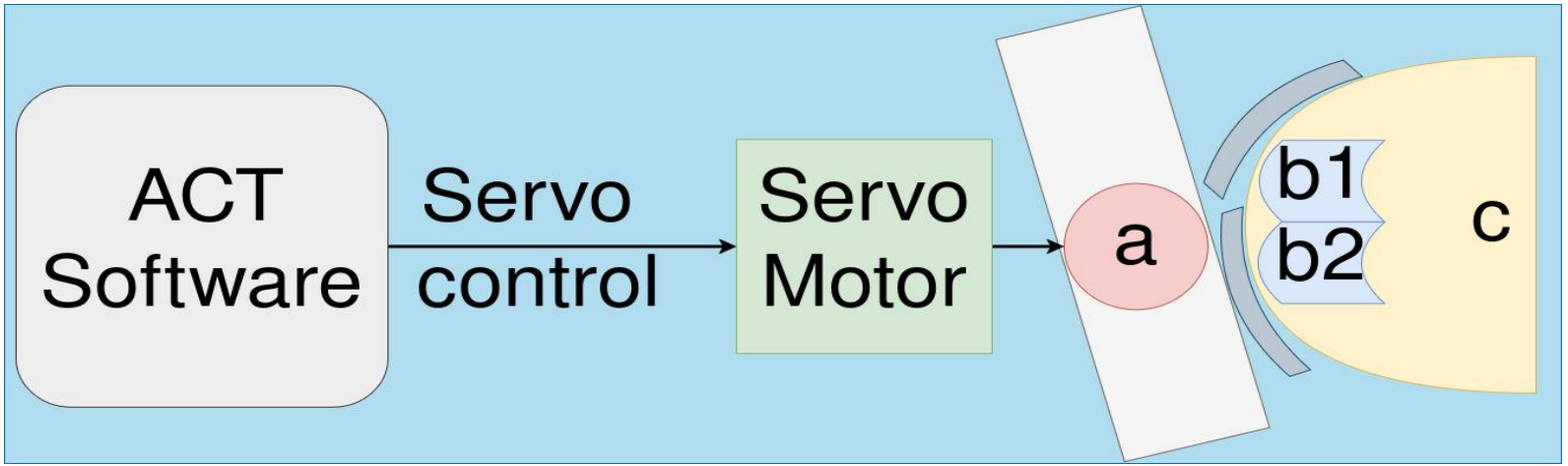
- Motors - An actuator for motion in CPS.
- A camera to detect the motion and the RPM.
- Same filter method as the LED test case. Two dots, a central dot and a dot on the spoke.
- The relative angle using centroid method determines the number of rotations.
- Highly dependent on frame rate of the camera and resolution.

Test Case - Motors



Test Cases - Bump Sensor and display

- Bump sensors – Used for robot navigation.
- Reflectance sensors that determine the bump using change of light intensity.
- Using a servo motor to angle a small rod to cause the bump sensor to activate.
- Display gives the output for each bump.
- We use an OCR to read the output displayed on the screen.



Hardware Faults in Bump Sensor

Fault Classes	Types of Faults	Tested Sensors and Reported Results			Display Status	Diagnosis
		Left Bump	Right Bump	Both Bumps		
HW Fault	Left sensor fault	No response	Responds to right bump	Responds only to right bump	Partial or missing data	Left Bump HW fault
	Right sensor fault	Responds to left bump	No response	Responds only to left bump	Partial or missing data	Right Bump HW fault
	Display fault	Normal detection	Normal detection	Normal detection	No display output	Display is faulty
	Both sensors or the display are faulty	Partial or no output	Partial or no output	Partial or no output	Partial or no output	Both sensors are faulty

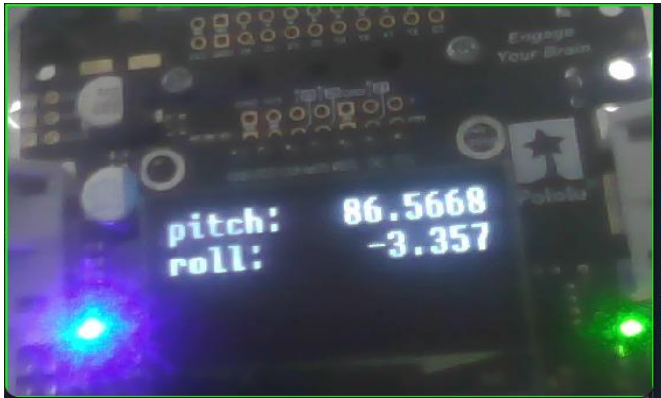
- Display is also tested along with IMU, so when there are ambiguous output, we can eliminate the faulty working of display using the IMU test.

Software Faults in Bump Sensor

Fault Classes	Types of Faults	Tested Sensors and Reported Results			Display Status	Diagnosis
		Left Bump	Right Bump	Both Bumps		
SW Fault	Left sensor mapped right	Right bump reported	Right bump reported	Right bump reported	Normal	Left sensor mapping error
	Right sensor mapped left	Left bump reported	Left bump reported	Left bump reported	Normal	Right sensor mapping error
	Both sensors mapped wrong	No bump	No bump	No bump	No bump	No response
Normal	No fault injected	Left bump	Right bump	Left and Right	Normal	No faults

Test Cases - IMU and display

- IMU sensors – navigation and orientation of the robot. Very prevalent in robotic systems.
- Use a pan and tilt platform that is calibrated to tilt to a certain random angle.
- The display shows the angle that is calculated from the sensor output.
- We use an OCR to read the output displayed on the screen.
- Additional steps here – fetching the pitch and roll values correctly.




```
---Output ---

Detected: 33 (Confidence: 0.42)
Detected: 28003 (Confidence: 0.14)
Detected: 86.5668 (Confidence: 0.95)
Detected: pitchf (Confidence: 0.73)
Detected: -3.357 (Confidence: 0.56)
Detected: roll. (Confidence: 0.39)

Pitch: 86.5668 (Conf 0.95)
Roll:  -3.357 (Conf 0.56)
Camera released and windows closed.
```

Fault Detection in IMU

Mode	Measured Pitch	Actual Pitch	Measured Roll	Actual Roll	Check
Normal	24.14	25.00	0.20	0.00	Passed
Normal	0.00	0.00	26.07	25.00	Passed
Normal	10.73	10.00	0.36	0.00	Passed
Faulty	217.81	20.00	2.96	0.00	Failed
Faulty	26.56	0.00	208.10	20.00	Failed
Faulty	45.05	0.00	-400.45	-20.00	Failed

- Fault injection here was through software since a faulty sensor would also give erratic values.

GitHub Actions Flow

- The actions are triggered using conditions specified in the yml file in the workflow directory of the respective repository.
- The flow of the GitHub actions for testing can be thought of as four categories.

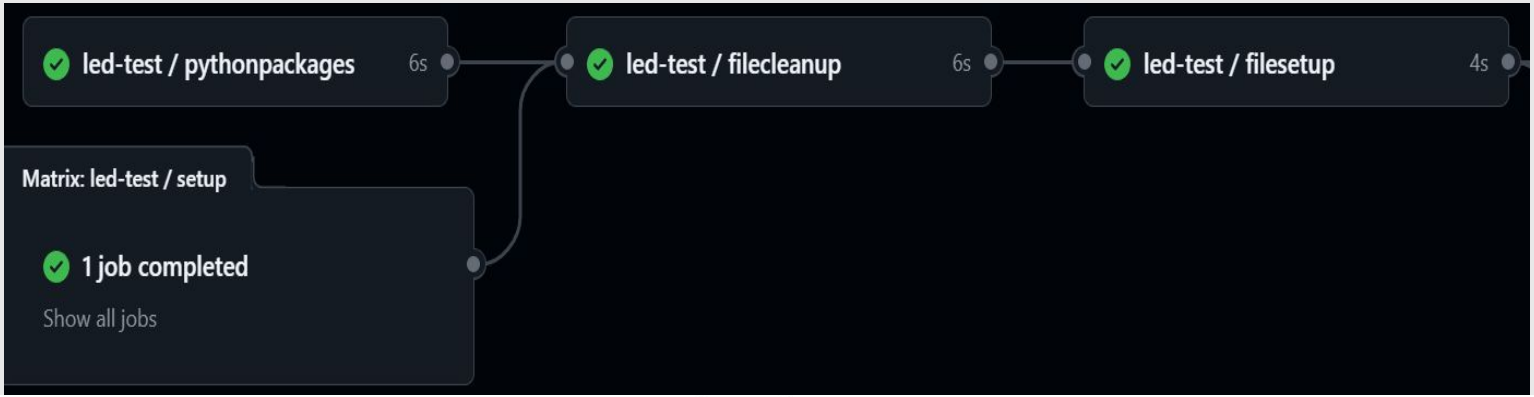
1. Setup
2. Compilation
3. Execution
4. Reporting

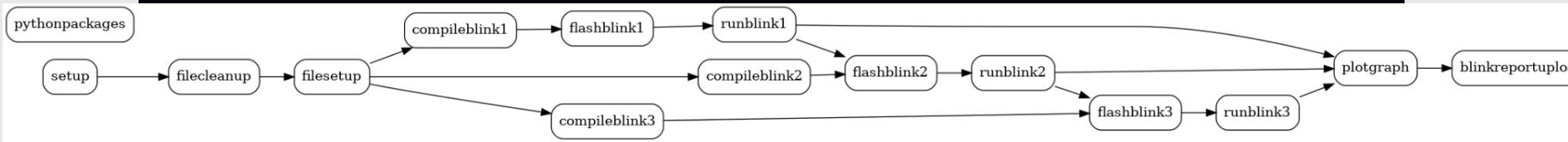
1. Setup

2. Compilation

3. Execution

4. Reporting



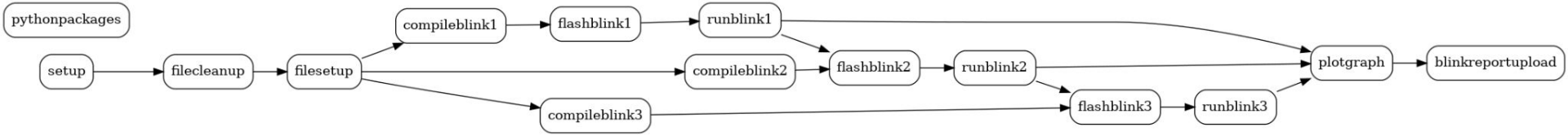


1. Setup

2. Compilation

3. Execution

4. Reporting



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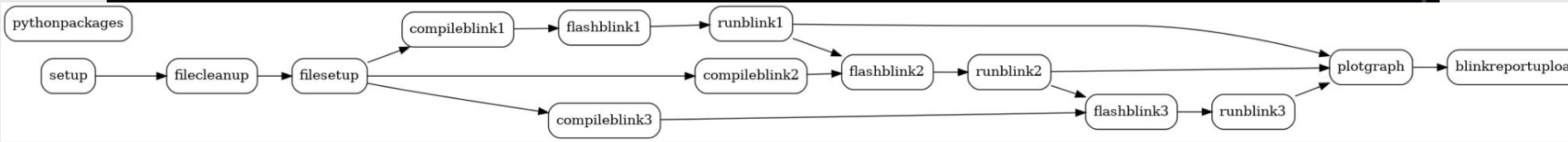

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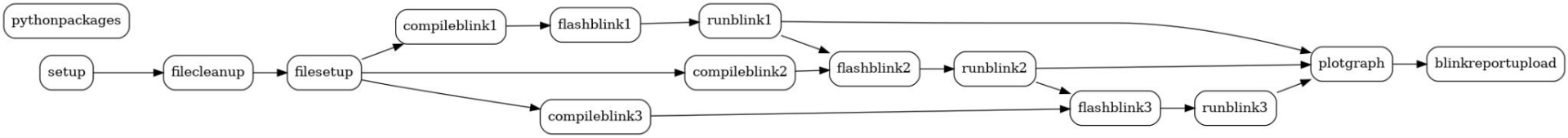

Future Work

- Security of the runner and robot. – Raspberry Pi as a physical representation of a VM.
- Creating a rate limiting check or safeguards which prevent the other tests or users from being starved of the hardware.
- Agents to be deployed to take care of repetitive actions.
- Understanding the battery performance or efficiency of the robot.
- Testbed hardware improvements.

Conclusion

- This study is aimed at creating a testbed that can test the behavior and performance of a CPS after a firmware upgrade or a toolchain change.
- The primary aim is to make educational open-source platforms safe and secure.
- Addressing the tedious testing process for CPS in the CI/CD pipeline.

Questions and Discussions

FIN

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ASU KIM Lab: https://labs.engineering.asu.edu/kim/

LF Embedded Systems Labs: https://www.lf-lang.org/embedded-lab/

ACT Repo: https://github.com/lf-lang/act-lf-testbed

Arizona State University

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KNOWLEDGEABLE & INTERACTIVE MACHINES

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