Secure PLC Coding Practices: Top 20 List

Version 1.0 (15 June 2021)

PLC Security TOP 20 LIST

1. Modularize PLC Code

Split PLC code into modules, using different function blocks (sub-routines). Test modules independently.

2. Track operating modes

Keep the PLC in RUN mode. If PLCs are not in RUN mode, there should be an alarm to the operators.

3. Leave operational logic in the PLC wherever feasible

Leave as much operational logic e.g., totalizing or integrating, as possible directly in the PLC. The HMI does not get enough updates to do this well.

4. Use PLC flags as integrity checks

Put counters on PLC error flags to capture any math problems.

5. Use cryptographic and / or checksum integrity checks for PLC code

Use cryptographic hashes, or checksums if cryptographic hashes are unavailable, to check PLC code integrity and raise an alarm when they change.

6. Validate timers and counters

If timers and counters values are written to the PLC program, they should be validated by the PLC for reasonableness and verify backward counts below zero.

7. Validate and alert for paired inputs / outputs

If you have paired signals, ensure that both signals are not asserted together. Alarm the operator when input / output states occur that are physically not feasible. Consider making paired signals independent or adding delay timers when toggling outputs could be damaging to actuators.

8. Validate HMI input variables at the PLC level, not only at HMI

HMI access to PLC variables can (and should) be restricted to a valid operational value range at the HMI, but further cross-checks in the PLC should be added to prevent, or alert on, values outside of the acceptable ranges which are programmed into the HMI.

9. Validate indirections

Validate indirections by poisoning array ends to catch fence-post errors.

10. Assign designated register blocks by function (read/write/validate)

Assign designated register blocks for specific functions in order to validate data, avoid buffer overflows and block unauthorized external writes to protect controller data.

11. Instrument for plausibility checks

Instrument the process in a way that allows for plausibility checks by cross-checking different measurements.

12. Validate inputs based on physical plausibility

Ensure operators can only input what's practical or physically feasible in the process. Set a timer for an operation to the duration it should physically take. Consider alerting when there are deviations. Also alert when there is unexpected inactivity.

13. Disable unneeded / unused communication ports and protocols

PLC controllers and network interface modules generally support multiple communication protocols that are enabled by default. Disable ports and protocols that are not required for the application.

14. Restrict third-party data interfaces

Restrict the type of connections and available data for 3rd party interfaces. The connections and/or data interfaces should be well defined and restricted to only allow read/write capabilities for the required data transfer.

15. Define a safe process state in case of a PLC restart

Define safe states for the process in case of PLC restarts (e.g., energize contacts, de-energize, keep previous state).

16. Summarize PLC cycle times and trend them on the HMI

Summarize PLC cycle time every 2-3 seconds and report to HMI for visualization on a graph.

17. Log PLC uptime and trend it on the HMI

Log PLC uptime to know when it's been restarted. Trend and log uptime on the HMI for diagnostics.

18. Log PLC hard stops and trend them on the HMI

Store PLC hard stop events from faults or shutdowns for retrieval by HMI alarm systems to consult before PLC restarts. Time sync for more accurate data.

19. Monitor PLC memory usage and trend it on the HMI

Measure and provide a baseline for memory usage for every controller deployed in the production environment and trend it on the HMI.

20. Trap false negatives and false positives for critical alerts

Identify critical alerts and program a trap for those alerts. Set the trap to monitor the trigger conditions and the alert state for any deviation.

About the Secure PLC Programming project

1. Modularize PLC Code

Split PLC code into modules, using different function blocks (sub-routines). Test modules independently.

Security Objective	Target Group
Integrity of PLC logic	Product Supplier

Guidance

Do not program the complete PLC logic in one place e.g., in the main Organization Block or main routine. Instead, split it into different function blocks (sub-routines) and monitor their execution time and their size in Kb.

Create separate segments for logic that functions independently. This helps in input validation, access control management, integrity verification etc.

Modularized code also facilitates testing and keeping track of the integrity of code modules. If the code inside the module has been meticulously tested, any modifications to these modules can be verified against the hash of the original code, e.g., by saving a hash of each of these modules (when that's an option in the PLC). This way, modules can be validated during the FAT/SAT or if the integrity of the code is in question after an incident.

Example

Gas Turbine logic is segregated into "startup", "Inlet Guide Vanes Control", "Bleed Valve Control" etc. so that you can apply standard logic systematically. This also helps in troubleshooting quickly if there were to be a security incident.

Custom function blocks that are tested rigorously can be re-used without alteration (and alerted if change attempts are made) and locked against abuse/misuse with a password/digital signature.

Why?

Beneficial for…?	Why?
Security	Facilitates the detection of newly added portions of code that could be malicious. Helps in logic standardization, consistency, and locking against unauthorized modifications.
Reliability	Helps control the program flow sequence and avoid loops, which could cause the logic to not react properly or crash.
Maintenance	Modular code is not only easier to debug (modules can be tested independently) but also easier to maintain and update. Also, the modules may be used for additional PLCs, thus allowing for common code to be used and identified in separate PLCs. This can aid maintenance personnel with quickly recognizing common modules during troubleshooting.

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic:** TA002 - Execution **Technique:** T0844 - Program Organization Units
ISA 62443-3-3	**SR 3.4**: Software and information integrity
ISA 62443-4-2	**CR 3.4**: Software and information integrity
ISA 62443-4-1	**SI-2**: Secure coding standards
MITRE CWE	**CWE-1120:** Excessive Code Complexity **CWE-653:** Insufficient Compartmentalization

2. Track operating modes

Keep the PLC in RUN mode. If PLCs are not in RUN mode, there should be an alarm to the operators.

Security Objective	Target Group
Integrity of PLC logic	Integration / Maintenance Service Provider Asset Owner

Guidance

If PLCs are not in RUN mode (e.g., PROGRAM mode), their code could be changed to track the RUN mode. Some PLCs have a checksum to alert for code changes, but if they do not, there's at least an indirect indicator of a potential issue while tracking operating modes:

- If PLCs are not in RUN mode, there should be an alarm to the operators. If they are aware that someone is supposed to be working on that control system, they can acknowledge the alarm and move on.
- The HMI should be configured to re-alert the operator toward the end of the shift about the presence of the alarm. The goal should be to keep track of any staff or contractors in the plant doing work that might impact the process.

Exception case: If the plant is in a testing or development phase, consider disabling this alarm but the plant should be isolated from higher levels of the network.

Example

If the PLC does not have a hardware switch for changing operating modes, it is recommended to at least make use of software mechanisms that can restrict changing PLC code, e.g., password protection in engineering software for reading and writing PLC code.

Why?

Beneficial for…?	Why?
Security	The operating mode (run / edit / write; for Allen Bradley PLCs: RUN / PROGram / REMote) determines if PLC can be tampered with. If the key-switch is in REMote state, it is technically possible to make changes to the PLC program over the communication interfaces even if the PLC is running.
Reliability	/
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA009 - Inhibit Response Function **Technique:** T0858 - Utilize/Change Operating Mode
ISA/IEC 62443-4-1	**SI-1** : Security implementation review

3. Leave operational logic in the PLC wherever feasible

Leave as much operational logic e.g., totalizing or integrating, as possible directly in the PLC. The HMI does not get enough updates to do this well.

Security Objective	Target Group
Integrity of PLC logic	Product Supplier Integration / Maintenance Service Provider Asset Owner

Guidance

HMIs provide some level of coding capabilities, originally aimed to help operators enhance visualization and alarming, that some programmers have employed to create code that should rather stay in the PLC to remain complete and auditable.

Calculating values as close to the field as possible makes these calculations more accurate. The HMI does not get enough updates to do totalizing / integrating well. Also, there is always latency between HMI and PLC. Further, when the code is in the PLC, and an HMI restarts, it can always receive totalizers/counts from a PLC.

In particular, HMI code to be avoided is anything related to security or safety functions such as interlocks, timers, holds or permissives.

For analyzing process data values over time, a process data historian is the better choice than the HMI. Use queries in a process historian database to compare totalized values (over a period, over a batch, over a process cycle) with totals aggregated locally in PLC logic. Alert on a variance greater than that can be explained by differences in data granularity.

Example

- Code to establish conditions to enable/disable buttons: Enable/disable actions should be controlled on PLC layer, otherwise, actions can be performed on the HMI (or through network) in PLC, although not meeting (intended) conditions.
- Timers to allow actions to the operator (delay timer for consecutive motor starts, timer to consider valves closed/open or motor stopped) should not be put on the HMI layer but in the PLC governing such motor/valve.
- Thresholds for alarms have to be part of PLC codes although displayed on HMIs.
- Water tank with changing volume: The PLC which controls flow in and out of the tank can easily totalize volume (and cross-validate totals). The HMI could do this as well, but it would need to get the values from the PLC first. These values would need accurate time-stamps in order to get correct totals in case of latency or and might miss values if the HMI restarts.

Why?

Beneficial for…?	Why?
Security	**1.** Allows consistency in verifying code changes. HMI coding has its change control apart from PLC, generally not with the same rigor (especially in construction and commissioning phases), not allowing system owners to have a complete view and even losing important considerations. HMI’s do not include “forced signals” or changed value lists as PLCs or SCADAs, so HMI level changes

Beneficial for...?	Why?
	are more difficult to be detected, practically impossible to be part of an authorization change management plan. **2.** For an attacker, it is harder to manipulate totals distributed over many PLCs than to manipulate totals all calculated in the HMI. **3.** If a portion of the enable/disable functions are not in the PLC, attackers might be able to manipulate the PLC and I/O without having to work the HMI portion as the proper information is already obfuscated on the operator screen.
Reliability	**1.** Calculations are more efficient and accurate if closer to the field. Also, totals and counts will still be available if HMI restarts (PLCs do not restart as often and usually store these values in non-volatile memory). **2.** Different sources for inputs and interlocks may mean non expected failures. There can be different technologies for HMIs in a plant (SCADA layer, but also field controller panels) and changes in one of those will fail to be disseminated through the rest of layers, leading to inconsistences in visualization and possible failures in operation.
Maintenance	Coding is easy to understand and transfer from PLC to PLC, not so much from HMIs to HMIs.

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter
ISA 62443-3-3	**SR 3.6** : Deterministic Output
ISA 62443-4-2	**CR 3.6** : Deterministic Output

4. Use PLC flags as integrity checks

Put counters on PLC error flags to capture any math problems.

Security Objective	Target Group
Integrity of PLC logic	Product Supplier Integration / Maintenance Service Provider

Guidance

If the PLC code was working fine but suddenly does a divide by zero, investigate. If something is communicating peer to peer from another PLC and the function/logic does a divide by zero when it wasn't expected, investigate.

Most programmers will ignore the issue as a math error or worse yet, might presume their code is perfect and let the PLC enter a hard fault state. During code development, engineers need to test and validate their code modules (snippets or routines) by inputting data outside of expected bounds. This may be termed Unit Level Test.

Assign different, locked memory segments for firmware, logic and protocol stack. Test the protocol stack for abuse cases. Abuse cases could be peculiar flag conditions in a packet header.

Example

PLC faults caused by out of bounds data are very common. This happens, for example, when an input value causes array indices go out of bounds, or timers with negative presets, or divide by zero exceptions.

Typical flags of interest are

- divide by zero
- counter overflow
- negative counter or timer preset
- I/O scan overrun

Why?

Beneficial for…?	Why?
Security	Attacks on PLCs could include changing its logic, activating a new program, testing new code, loading a new process recipe, inserting auxiliary logic to send messages or activating some feature. Since most PLCs do not provide cryptographic integrity checks, flags can be a good indicator if one of the above logic changes happens.
Reliability	Flags taken seriously can avoid the PLC running with programming or I/O errors. Also, if an error occurs, the source of the failure is more obvious.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic** : TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter
ISA 62443-3-3	**SR 3.5**: Input Validation **SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.5**: Input Validation **CR 3.6**: Deterministic Output
ISA 62443-4-1	**SI-2**: Secure coding standards **SVV-1**: Security requirements testing
MITRE CWE	**CWE-128:** Wrap-around **CWE-190:** Integer Overflow **CWE-369:** Divide by Zero **CWE-754:** Improper Check for Unusual or Exceptional Conditions

5. Use cryptographic and / or checksum integrity checks for PLC code

Use cryptographic hashes, or checksums if cryptographic hashes are unavailable, to check PLC code integrity and raise an alarm when they change.

Security Objective	Target Group
Integrity of PLC logic	Product Supplier Integration / Maintenance Service Provider Asset Owner

Guidance

A) Checksums

Where (cryptographic) hashes are not feasible, checksums may be an option. Some PLCs generate a unique Checksum when code is downloaded into the PLC Hardware. The Checksum should be documented by the manufacturer / integrator after SAT and be part of warranty / service-conditions.

If the checksum feature is not natively available in the controller, this can also be generated in the EWS/HMI and probed e.g., once a day to compare with the hash of the original code in the PLC to verify that they are matching. While this won't provide real time alerts, it's good enough to track if anyone is attempting changes to the PLC code.

The checksum value can also be moved into a PLC register and configured for an alarm when it changes, the value can be sent to historians etc.

B) Hashes

PLC CPUs generally do not have the processing capacity to generate or check hashes while running. Attempting a hash might actually cause the PLC to crash. But the PLC's engineering software might be able to calculate hashes from the PLC code and save them either in the PLC or somewhere else in the control system.

Example

PLC vendors that are known to have checksum features:

- Siemens (see example)
- Rockwell

Also, external software can be used for generating checksums:

- Version dog
- Asset Guardian
- PAS

Siemens implementation example

Example for creating checksums in Siemens S7-1500 PLC:

GetChecksum-Function Block reads actual checksum and with a lightweight script the "SAT-Checksum" can be stored as reference. A deviance from the Reference-Checksum can be stored with the Datalog-Function.

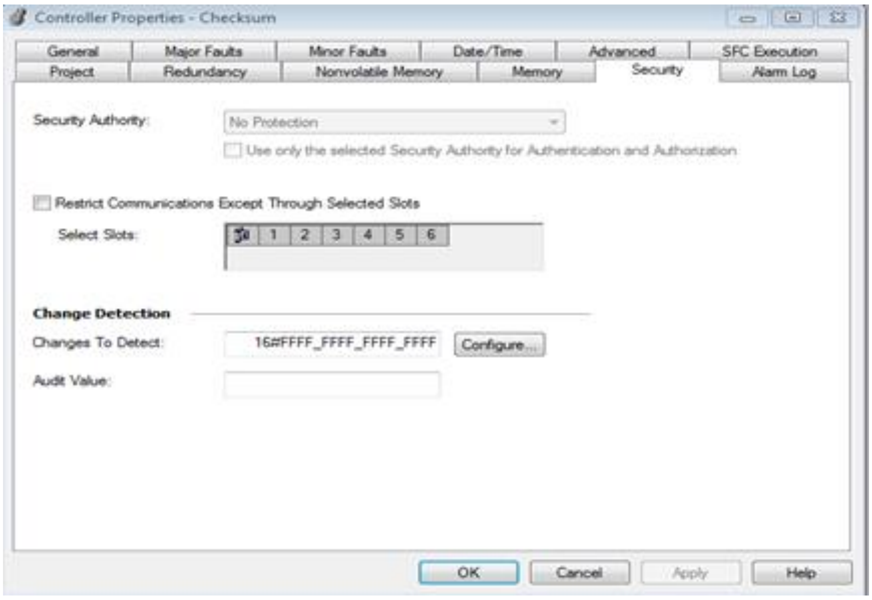
	Date	UTC Time	Referenz	Aktuell
1	11/21/2019	9:55:11	84 2A 76 DF 5B 31 F4 16	FF 2C EA 71 44 D7 81 04
2	11/21/2019	9:57:33	FF 2C EA 71 44 D7 81 04	FF 2C EA 71 44 D7 81 04
3	11/21/2019	9:58:17	FF 2C EA 71 44 D7 81 04	5B 7C 57 7E E2 3E EF C3
4	11/21/2019	9:58:36	FF 2C EA 71 44 D7 81 04	5B 7C 57 7E E2 3E EF C3
5	11/21/2019	9:58:44	5B 7C 57 7E E2 3E EF C3	5B 7C 57 7E E2 3E EF C3

Rockwell Implementation Example:

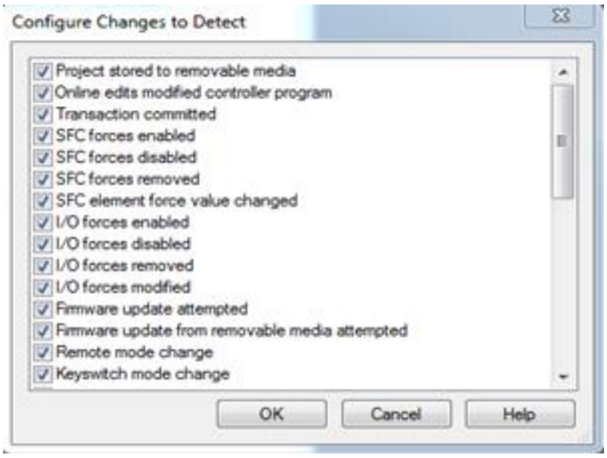
This is partial example of how an organization can develop a level of PLC program change detection capability within their ICS environment. This example is specifically for a Rockwell Automation ControlLogix PLC and is not complete; however, it illustrates how to retrieve the PLC processor state into a register within the PLC. Once in a register in the PLC, the organization can use it create a configuration change alarm for display on an HMI, transmit the raw state information to an HMI for trending and monitoring, or send it to a Historian for long term capture.

This practice provides an opportunity, using existing tools and capabilities, to gain situational awareness of when critical cyber assets change. It is up to the organization to complete the use of this example in a method that works best in their environment.

1. From the Controller Properties Dialog Box, select the configure button on “Change to Detect”



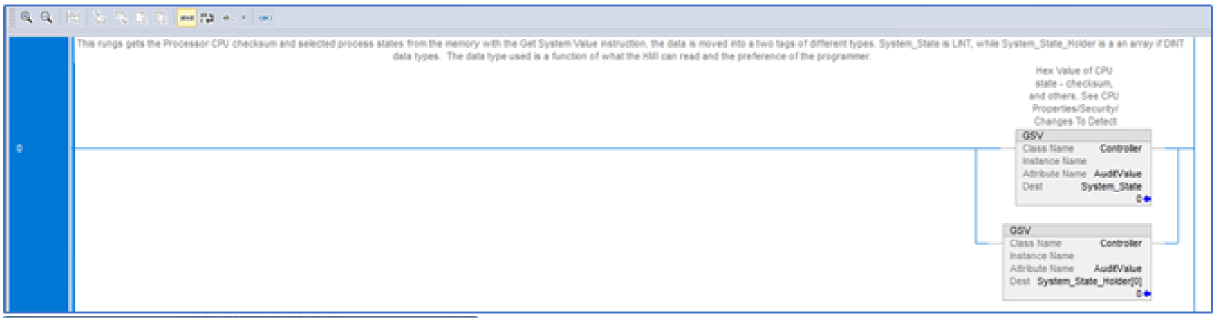
2. Within the selection window, choose all items to be monitored

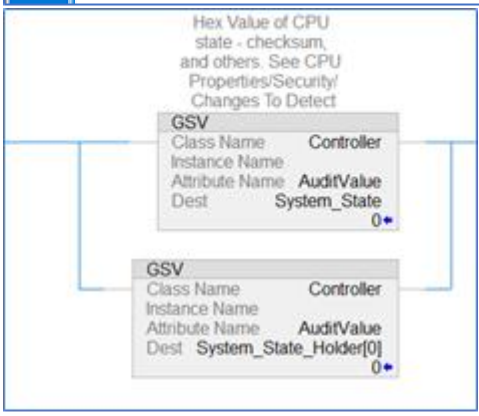


3. Create a Tag to receive the processor state information. This tag can be of type “LINT” or a 2-word array of type “DINT”

Name	Alias For	Base Tag	Data Type	Description	External Access	Constant	Style
System_State			LINT	Hex Value of CPU stat...	Read/Write	☐	Decimal
System_State_Hol...			DINT[4]		Read/Write	☐	Decimal
						☐	

4. Use the Get System Values (GSV) instruction to get the processor state information from memory and move it into a Tag that can be used in logic or read at the HMI





Why?

Beneficial for…?	Why?
Security	Knowing if PLC code was tampered with is essential for both noticing a compromise and verifying if a PLC is safe to operate after a potential compromise.
Reliability	Hashes or checksums can also be a means to verify if the PLC is (still) running code approved by the integrator / manufacturer.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA002 - Execution, TA010 - Impair Process Control **Technique:** T0873 - Project File Infection, T0833 - Modify Control Logic
ISA 62443-3-3	**SR 3.4** : Software and information integrity
ISA 62443-4-2	**CR 3.4** : Software and information integrity **EDR 3.12** : Provisioning product supplier roots of trust
ISA 62443-4-1	**SI-1** : Security implementation review **SVV-1** Security requirements testing
MITRE CWE	**CWE-345:** Insufficient Verification of Data Authenticity • **(child) CWE-353:** Missing Support for Integrity Check • **(child) CWE-354:** Improper Validation of Integrity Check Value

6. Validate timers and counters

If timers and counters values are written to the PLC program, they should be validated by the PLC for reasonableness and verify backward counts below zero.

Security Objective	Target Group
Integrity of PLC variables	Integration / Maintenance Service Provider Asset Owner

Guidance

Timers and counters can technically be preset to any value. Therefore, the valid range to preset a timer or counter needs to should be restricted to meet the operational requirements.

If remote devices such as an HMI write timer or counter values to a program:

- do not let the HMI write to the timer or counter directly but go through a validation logic
- validate presets and timeout values in the PLC

Validation of timer and counter inputs is easy to directly do in the PLC (without the need for any network device capable of Deep Packet Inspection), since the PLC “knows” what the process state or context is. It can validate “what’ it gets and “when” it gets the commands or setpoints.

Example

During PLC startup, timers and counters are usually preset to certain values.

If there is a timer that triggers alarms at 1.3 seconds, but that timer is preset maliciously to 5 minutes, it might not trigger the alarm.

If there is a counter that causes a process to stop when it reaches 10,000 but that is set it to 11,000 from the beginning, the process might not stop.

Why?

Beneficial for…?	Why?
Security	If I/O, timers, or presets are written directly to I/O, not being validated by the PLC, the PLC validation layer is evaded and the HMI (or other network devices) are assigned an unwarranted level of trust.
Reliability	The PLC can also validate when an operator accidentally presets bad timer or counter values.
Maintenance	Having valid ranges for timers and counters documented and automatically validated may help when updating logic.

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic** : TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter
ISA 62443-3-3	**SR 3.5** : Input Validation
ISA 62443-4-2	**CR 3.5** : Input Validation
ISA 62443-4-1	**SI-2** : Secure coding standards **SVV-1** : Security requirements testing

7. Validate and alert for paired inputs / outputs

If you have paired signals, ensure that both signals are not asserted together. Alarm the operator when input / output states occur that are physically not feasible. Consider making paired signals independent or adding delay timers when toggling outputs could be damaging to actuators.

Security Objective	Target Group
Integrity of PLC variables Resilience	Product Supplier Integration / Maintenance Service Provider

Guidance

Paired inputs or outputs are those that physically cannot happen at the same time; they are mutually exclusive. Though paired signals cannot be asserted at the same time unless there is a failure or malicious activity, PLC programmers often do not prevent that assertion from happening.

Validation is easiest to directly do in the PLC, because the PLC is aware of the process state or context. Paired signals are easier to recognize and track if they have sequential addresses (e.g., input 1 and input 2).

Another scenario where paired inputs or outputs could cause problems is when they are not asserted at the same time, but toggled quickly in a way that damages actuators.

Example

Examples of paired signals:

- START and STOP
  - Independent start & stop: Configure start and stop as discrete outputs instead of having a single output that can be toggled on/off. By design, this does not allow simultaneous triggers. For an attacker, it is way more complicated to rapidly toggle on / off if two different outputs have to be set.
  - Timer for restart: Also consider adding a timer for a re-start after a stop is issued to avoid rapid toggling off start/stop signals.
- FORWARD and REVERSE
- OPEN and CLOSE

Examples for toggling paired signals that could be damaging:

If the PLC / MCC accepts a discrete input, this provides an easy option for an attacker to cause physical damage on actuators. The well-known scenario for toggling outputs to do damage would be an MCC, but this practice applies to all scenarios where toggling outputs could do damage. A proof of concept where rapidly toggling outputs could cause real damage was the Aurora Generator Test in 2007 conducted by the Idaho National Laboratory, where toggling outputs out of sync caused circuit breaker damage.

Why?

Beneficial for…?	Why?
Security	1. If PLC programs do not account for what is going to happen if both paired input signals are asserted at the same time, this is a good attack vector. 2. Both paired input signals being asserted is a warning that there is an operational error, programming error, or something malicious is going on. 3. This avoids an attack scenario where physical damage can be caused to actuators.
Reliability	1. Paired input signals can point to a sensor being broken or mis-wired or that there is a mechanical problem like a stuck switch. 2. Quickly toggling start and stop could also be done by mistake, so this also prevents damage that might be done inadvertently.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter, T0806 - Brute Force I/O
ISA 62443-3-3	**SR 3.5**: Input Validation **SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.5**: Input Validation **CR 3.6**: Deterministic Output
ISA 62443-4-1	**SI-2**: Secure coding standards **SVV-1**: Security requirements testing
MITRE CWE	**CWE-754:** Improper Check for Unusual or Exceptional Conditions

8. Validate HMI input variables at the PLC level, not only at HMI

HMI access to PLC variables can (and should) be restricted to a valid operational value range at the HMI, but further cross-checks in the PLC should be added to prevent, or alert on, values outside of the acceptable ranges which are programmed into the HMI.

Security Objective	Target Group
Integrity of PLC variables	Product Supplier Integration / Maintenance Service Provider

Guidance

Input validation could include out-of-bounds checks for valid operational values as well as valid values in terms of data types that are relative to the process.

If a PLC variable receives a value that is out-of-bounds, provide PLC logic to either

- input a **default value** to that variable which does not negatively affect the process, and can be used as a flag for alerts, or
- input the **last correct value** to that value and log the event for further analysis.

Example

Example 1

An operation requires a user to input a value on an HMI for valve pressure. Valid ranges for this operation are 0-100, and the user's input is passed from the user input function on the HMI to the V1 variable in the PLC. In this case,

1. HMI input to variable V1 has a restricted range of 0-100 (dec.) programmed into the HMI.
2. The PLC has a cross-check logic that states:

```
IF V1 < 0 OR IF V1 > 100, SET V1 = 0.
```

This provides a positive response of a presumably safe value to an invalid input to that variable.

Example 2

An operation requires user input for measurement thresholds to a variable which should always be within an INT2 data range. The user input is passed from the HMI into the V2 variable in the PLC, which is a 16-bit data register.

1. HMI input to variable V2 has a restricted range of -32768 to 32767 (dec.) programmed into the HMI.
2. The PLC has data-type cross-check logic that monitors the overflow variable (V3), which exists just after V2 in the PLC's memory structure:

```
IF V2 = -32768 OR IF V2 = 32767 AND V3 != 0,

SET V2 = 0 AND SET V3 = 0 AND SET DataTypeOverflowAlarm = TRUE.
```

Example 3

Scale PV (Process Value), SP (Set Point) and CV (Control Variable) for PID (Proportional, Integral, Derivative controller) to consistent or raw units to eliminate scaling errors causing control problem. Incorrect scaling might lead to inadvertent abuse cases.

Why?

Beneficial for…?	Why?
Security	**1.** While HMIs typically provide some sort of input validation, a malicious actor can craft or replay modified packets to send arbitrary values to the variables in the PLC which are open to outside influence (open to values passed from an HMI, for example). **2.** PLC protocols are typically marketed as “open” protocols and published to the general public, so creating malware that utilizes “open” protocol information can be trivial to develop. PLC variable mapping can typically occur through traffic analysis during the reconnaissance phases of an attack, thus providing the intruder with the necessary information to craft malicious traffic to the target and thereby manipulate a process with unauthorized tools. Cross-checking values passed into the PLC before implementing that data into the process ensures valid data ranges and mitigates an invalid value in those memory locations by forcibly setting safe ranges when a value is detected as out-of-bounds during the course of the PLC scan.
Reliability	/
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter
ISA 62443-3-3	**SR 3.5**: Input Validation **SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.5**: Input Validation **CR 3.6**: Deterministic Output
ISA 62443-4-1	**SI-2**: Secure coding standards **SVV-1**: Security requirements testing
MITRE CWE	**CWE-1320:** Improper Protection for Out of Bounds Signal Level Alerts

9. Validate indirections

Validate indirections by poisoning array ends to catch fence-post errors.

Security Objective	Target Group
Integrity of PLC variables	Product Supplier Integration / Maintenance Service Provider

Guidance

An indirection is the use of the value of a register in another register. There are many reasons to use indirections.

Examples for necessary indirections are:

- Variable frequency drives (VFDs) that trigger different actions for different frequencies using lookup tables.
- To decide which pump to start running first based on their current run times

PLCs do not typically have an "end of an array" flag so it's a good idea to create it in software; the goal is to avoid unusual/unplanned PLC operations.

Example

Instruction List (IL) Programming

The approach can be turned into a few function blocks and possibly even reused for other applications.

1. **Create array mask**

Check if the array is binary-sized. If it is not binary-sized, create a mask to the next size up on a binary scale. e.g., if you have a need for 5 registers (not binary-sized):

```
[21 31 41 51 61]
```

define an array of 8:

```
[x x 21 31 41 51 61 x]
```

Next, take the index value to pick up for the indirection - in this example, it is 3.

Caveat: Index begins at 0!

```
[21 31 41 51 61]
____________^
```

Index: `3`

add an offset to it making up for the poisoned end. The offset can be 1 or higher, in this case it is 2:

```
[x x 21 31 41 51 61 x]
_________________^
```

Index including offset: `3 + 2 = 5`

and then AND the index including offset with a mask that equals the array size.
In this example the array size is 8, thus index 7, so the mask would be 0x07. The mask makes sure the maximum index you can get is 7, for example:

`6 AND 0x07` would give back 6.
`7 AND 0x07` would give back 7
`8 AND 0x07` would give back 0.
`9 AND 0x07` would give back 1.

This ensures you always address a value in the array.

2. Insert poisoned ends

Poisoning ends is optional. You would be able to detect manipulated indirections without the poisoning, but poisoning helps to catch fence-post errors because you get back a value that does not make sense.

The point is that at index 0 of the array, there should be a value that is invalid – such as -1 or 65535. This is “the poisoned end”. Likewise, at the last elements of the array you do the same:

So, for the array above, the poisoned version could look like this:

```
[-1 -1 21 31 41 51 61 -1]
```

3. Record value of indirection address without mask

Then record the value of the indirect address without AND mask and offset:
In this example, you’d record 51 for index 3.

```
[21 31 41 51 61]
____________^
_______Index 3
```

4. Execute AND mask and compare values (=indirection validation)

Compare your recorded value to the value after you have done the offset and the AND mask.

4a. Case A: Correct Indirection

First, offset:
Index + Offset = 3 + 2 = 5

Second, mask:
`5 AND 0x07 = 5`

Third, indirection check:

```
[-1 -1 21 31 41 51 61 -1]
____________________^
```

Index including offset: `5`
`Value = 51` equals the recorded value, so everything is fine.

4b. Case B: Manipulated Indirection

If you now had a manipulated indirection, let’s say 7, let us see what happens:

First, offset:
`Index + Offset = 7 + 2 = 9`

Second, mask:
`9 AND 0x07 = 1`

Third, indirection check:
```
[-1 -1 21 31 41 51 61 -1]
_____^
```

Index including offset: **1**

`Value =` **`-1`** does not equal the recorded value and also indicates your poisoned end, so you'd know your indirection is manipulated.

5. Execute fault / programmer alert

If this validated value is different from your recorded one, then you know something is wrong. Raise a software quality alarm.

Then, check the indirection value. If it is a poisoned value, you should raise another software quality alarm. This is an indication of a fence-post error.

Why?

Beneficial for…?	Why?
Security	Most PLCs do not have any feature to handle out-of-bounds indices for arrays. There are **two potentially dangerous scenarios** that can stem from indirection mistakes: **First**, if an indirection leads to reading from the wrong register, the program executes using wrong values. **Second**, if a wrong indirection leads to writing to the wrong register, the program overwrites code or values you want to keep. In both cases, indirection errors can be hard to spot and can have serious impacts. They can be caused by human error but also be inserted maliciously.
Reliability	Identifies non-malicious human errors in programming.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter
ISA 62443-3-3	**SR 3.5**: Input Validation **SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.5**: Input Validation **CR 3.6**: Deterministic Output
ISA 62443-4-1	**SI-2**: Secure coding standards **SVV-1**: Security requirements testing
MITRE CWE	**CWE-129:** Improper Validation of Array Index

10. Assign designated register blocks by function (read/write/validate)

Assign designated register blocks for specific functions in order to validate data, avoid buffer overflows and block unauthorized external writes to protect controller data.

Security Objective	Target Group
Integrity of PLC variables	Product Supplier Integration / Maintenance Service Provider

Guidance

Temporary memory, also known as scratch pad memory, is an easily exploitable area of memory if this practice is not followed. e.g., simply writing to a "Modbus" register that is out of bounds could lead to overwriting memory registers used for temporary calculations.

Generally, register memory can be accessed by other devices across the PLC network for read and write operations. Some registers could be read by an HMI, and others could be written by a SCADA system etc. Having specific register arrays for a certain application also makes it easier (in the controller or an external firewall is used) to configure Read only access from another device/HMI.

Examples of functions for which designated register blocks make sense are:

- reading
- writing (from HMI / Controller / other external device)
- validating writes
- calculations

Ensuring external writes to allowable registers also helps in avoiding main memory reset errors either due to out of bound execution or malicious attempts. These designated register blocks can be used as buffers for I/O, timer, and counter writes by validating that the buffer is completely written (does not contain part old, part new data) and validating all the data in the buffer.

Background:

Main memory and register memory are used differently. Main memory is used for storing currently executing program logic whereas the register memory is used as a temporary memory by the currently executing logic. Though register memory is a temporary one, since it is being used by the executing logic it is bound to contain some important variables that would affect the main logic.

Example

Examples for what could happen if this practice is not implemented:
(*Reference: G. P. H. Sandaruwan, P. S. Ranaweera, Vladimir A. Oleshchuk, PLC Security and Critical Infrastructure Protection*):

- Siemens typically uses the scratchpad memory in the flag area from flag 200.0 to flag 255.7. If a bit is changed within this area there is a likelihood of a serious malfunction of the PLC based on the importance of that bit or byte.
- Assume that an attacker can gain access to one of the machines in the PLC network and infect that machine with a worm which is capable of writing arbitrary values to the register

memory. Since the register memory values changed arbitrarily, it can change the pressure value.

- Executing logic will set a new value based on the change and that may cause the system to exceed its safety margins and possibly driven to a failure.

Examples for implementing this practice:

- In a scenario where there is a safety zone (but the DCS can read), the firewall can log any "write' attempts with a rule that these registers are READ ONLY in the safety zone.
- In another scenario, there could be some write-capable registers, and others are read only, but having all the READ ONLY registers in a single array makes it easier to configure them in the controller (or a firewall).

Why?

Beneficial for…?	Why?
Security	Makes it easier to protect the controller data by function (read/write/validate). Makes it easier for protocol sensitive firewalls to do their job: The rules get simpler because it is very clear what register blocks are allowed for the HMI to access. Makes it easier to manage the (simpler) rules in the firewall. Making unauthorized changes to internal temporary memory is an easily exploitable vulnerability (By-pass Logic Attack). When inputs and outputs to PLC routines are properly validated, any changes (by a malicious actor or by mistake) can be caught easily instead of staying in the logic sequence for long and throwing errors / causing issues later in execution.
Reliability	Makes reads and writes go faster because the number of transactions is reduced. Even authorized changes and programming mistakes can cause a malfunction if temporary memory is not protected. Network and communications errors on long messages can result in unintended errors if the validity of the data is not checked prior to processing.
Maintenance	Programming mistakes causing writing to temporary memory can make it hard to find errors, so the problem can be avoided by assigning specific registers for writes.

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic** : TA009 - Inhibit Response Function, TA010 - Impair Process Control **Technique:** T0835 - Manipulate I/O image , T0836 - Modify Parameter
ISA 62443-3-3	**SR 3.4** : Software and information integrity **SR 3.5** : Input Validation **SR 3.6** : Deterministic Output
ISA 62443-4-1	**SD-4**: Secure design best practices **SI-1**: Security implementation review **SI-2** : Secure coding standards **SVV-1** : Security requirements testing
ISA 62443-4-2	**CR 3.4** : Software and information integrity **CR 3.5** : Input Validation **CR 3.6** : Deterministic Output
MITRE CWE	**CWE-787:** Out-of-bounds Write **CWE-653:** Insufficient Compartmentalization

11. Instrument for plausibility checks

Instrument the process in a way that allows for plausibility checks by cross-checking different measurements.

Security Objective	Target Group
Integrity of I/O values	Product Supplier Integration / Maintenance Service Provider

Guidance

There are different ways of using physical plausibility for validating measurements:

a) Compare integrated and time-independent measurements

Plausibility checks can be done by integrating or differentiating time-dependent values over a period of time and comparing to time-independent measurements.

b) Compare different measurement sources

Also, measuring the same phenomenon in different ways can be a good plausibility check. Different measurement sources do not necessarily have to be different physical sensors, but can also mean using alternative communication channels (see examples).

Example

a) Compare integrated and time-independent measurements

- Metered pump and tank level gauge: volumetric change should equal integrated flow.
- Burner in a boiler: added caloric heat should equal temperature rise.

b) Compare different measurement sources

- Using air speed, artificial horizon, vertical speed, and altitude in the airplane to measure the phenomenon of the climbing / descending airplane.
- Comparing process parameter values from independent data loggers (tied into 4-20mA loops or relay contacts and transmitted via independent communication channels) to SCADA system data (coming in the “normal” way through PLC and HMI) and alerting on deviations and significantly off-specified values.

Why?

Beneficial for…?	Why?
Security	Facilitates monitoring for manipulated values (assuming not all sensors are manipulated at once).
Reliability	Prevents acceptance or identifies (for future action) corrupted / wrong measurements as inputs.
Maintenance	Rules out the possible physical causes for failures more quickly.

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0806 - Brute Force I/O
ISA 62443-3-3	**SR 3.5**: Input Validation **SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.5**: Input Validation **CR 3.6**: Deterministic Output
MITRE CWE	**CWE-754:** Improper Check for Unusual or Exceptional Conditions

12. Validate inputs based on physical plausibility

Ensure operators can only input what's practical or physically feasible in the process. Set a timer for an operation to the duration it should physically take. Consider alerting when there are deviations. Also alert when there is unexpected inactivity.

Security Objective	Target Group
Integrity of I/O values	Integration / Maintenance Service Provider

Guidance

a) Monitor expected physical durations

If the operation takes longer than expected to go from one extreme to the other, that is worthy of an alarm. Alternatively, if it does it too quickly, that is worthy of an alarm too.

A simple solution could be a step-timeout alert. This would be useful for sequence/step-controlled tasks.
For example, the step "move object from A to B" takes 5 sec from start of the step until the transition condition (sensor: object arrived at B) is met.
If the condition is met significantly too early or too late, the step-timeout is alert triggered.

b) Monitor expected physical repeating activity

Physical plausibility checking can also mean alert for physically implausible inactivity: If there is an expectation of a regular, repeating cycle of events (e.g., batches, diurnal patterns), an inactivity timer would alert if something which is expected to change (discrete or analog value) remains static for far too long.

Example

a) Monitor expected physical durations

- The gates on a dam takes a certain time to go from fully closed to fully open
- In a wastewater utility, a wet well takes a certain time to fill

b) Monitor expected physical repeating activity

- Manufacturing process or pipeline batching should regularly cycle between control ranges or operating modes.
- Municipal wastewater treatment plants typically have a diurnal cycle of activity / pattern of influent flow rates.

c) Limit operator entry for set points to what's practical/physically possible.

- e.g., Oldsmar Florida case allowed for operator input that's a) thousands of times more than what was typically needed b) that's physically not possible. Try to configure the operational limits in the PLC code wherever possible instead of using HMI scripts.

Why?

Beneficial for…?	Why?
Security	**1.** Deviations can indicate an actuator was already in the middle of a travel state or that someone is trying to fake the I/O, e.g., by doing a replay attack. **2.** Inactivity alerts facilitate monitoring for frozen or forced constant values which could be the result of system or device tampering.
Reliability	**1.** Deviations give you an early alert for broken equipment due electrical or mechanical failures. **2.** Inactivity alerts help flag measurements or system control loops which may be failing (thus static) due to physical device fault or an issue with the logic control algorithm or failed/improper operator input.
Maintenance	

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0806 - Brute Force I/O
ISA 62443-3-3	**SR 3.5**: Input Validation **SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.5**: Input Validation **CR 3.6**: Deterministic Output
MITRE CWE	**CWE-754:** Improper Check for Unusual or Exceptional Conditions

13. Disable unneeded / unused communication ports and protocols

PLC controllers and network interface modules generally support multiple communication protocols that are enabled by default. Disable ports and protocols that are not required for the application.

Security Objective	Target Group
Hardening	Integration / Maintenance Service Provider

Guidance

Common protocols usually enabled by default are e.g., HTTP, HTTPS, SNMP, Telnet, FTP, MODBUS, PROFIBUS, EtherNet/IP, ICMP, etc.

Best practice is to develop a data flow diagram that depicts the required communications between the PLC and other components in the system.

The data flow diagram should show both the physical ports on the PLC as well as the logical networks they are connected to. For each physical port, a list of required network protocols should be identified and all others disabled.

Example

For example, many PLCs include an embedded web server for maintenance and troubleshooting. If this feature will not be used, if possible, it should be disabled as this could be an attack vector.

Why?

Beneficial for...?	Why?
Security	Every enabled port and protocol add to the PLC's potential attack surface. The easiest way to make sure an attacker can't use them for unauthorized communication is to disable them altogether.
Reliability	If a PLC cannot communicate via a certain port or protocol, this also reduces the potential amount of (malformed) traffic, be it malicious or not, which decreases the chances of the PLC crashing because of unintended / malformed communication packages.
Maintenance	Disabling unused ports and protocols also facilitates maintenance, because it reduces the PLC's overall complexity. What's not there does not need to be administrated or updated.

References

Standard / framework	Mapping
MITRE ATT&CK for ICS	**Tactic**: TA005 - Discovery **Technique:** T0808 - Control Device Identification , T0841 - Network Service Scanning, T0854 - Serial Connection Enumeration
ISA 62443-3-3	**SR 7.6**: Network and security configuration settings **SR 7.7**: Least functionality
ISA 62443-4-2	**EDR 2.13** : Use of physical diagnostic and test interfaces
ISA 62443-4-1	**SD-4**: Secure design best practices **SI-1**: Security implementation review **SVV-1**: Security requirements testing

14. Restrict third-party data interfaces

Restrict the type of connections and available data for 3rd party interfaces. The connections and/or data interfaces should be well defined and restricted to only allow read/write capabilities for the required data transfer.

Security Objective	Target Group
Hardening	Integration / Maintenance Service Provider

Guidance

In some cases, due to long cable runs or a large exchange of data, interfaced data connections present a better business case than hard wired data exchange between two separate parties.

The following guidelines should be considered and followed where practical when designing and implementing a third-party data exchange interface:

- Use a dedicated communications module, either directly connected to the 3rd party PLC or data exchange equipment, or use dedicate network equipment physically segregated from each party's core network.
- The MAC address of connected devices is typically available in system variables for any ICS Ethernet-enabled device, making it possible to verify device identity with a multi-factor approach (IP address + MAC maker code = trusted device). This practice is certainly not fool-proof, as MAC & IP addresses can be spoofed, but it serves to raise the bar in terms of communications between trusted ICS systems and devices.
- When selecting a protocol for 3rd party interfaces, choose a protocol which minimizes the ability of the third party to write data to the owner's system.
- Choose a connection method and connection port which prevents the 3rd party from being able to configure the owner's PLC or data exchange equipment.
- The third party should not be able to read or write to any data that has not been explicitly defined and made available.
- Use a watchdog timer for monitoring communication so that commands are not sent to a PLC in fault mode.
- Serial Connection: Use a dedicated communication module for each 3rd party interface with a restricted array of data. Ensure the owner's side of the connection is the Initiator and that the third party is the Responder.
- Ethernet/IP: Some PLCs allow for communication modules to function as a firewall and can perform Deep Packet Inspection (DPI), or restrict communication module interfaces to limit the data exchange to a predefined subset. If these features are available, and an Ethernet/IP protocol is in use, ensure the features are enabled and configured.
- When operational or contractual requirements prevent the owner from accomplishing the previous items, consider using a separate "data concentrator" (aka proxy/DMZ) PLC in order to buffer the data and protect the owner from unwanted writes/programming from the 3rd party. Ensure the backplane of this PLC cannot be traversed from the 3rd party network.

Example

- Pipeline or Lease Automatic Custody Transfer (LACT) units which transfer and meter hydrocarbons or water exchanged between an upstream producing or pipeline company and a midstream pipeline company with network or serial interfaced connections sharing metering, state, and permissive information between companies.
- Regional potable water purveyor (importer) sharing turnout water flow rate being delivered to a local municipality's water plant.

Why?

Beneficial for…?	Why?
Security	1. Limit the exposure to 3rd party networks and equipment. 2. Authenticate external devices to prevent spoofing.
Reliability	Limits the ability for intentional or unintentional modifications or access from 3rd party locations or equipment.
Maintenance	

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic**: TA010 - Impair Process Control **Technique:** T0836 - Modify Parameter
ISA 62443-3-3	**SR 7.6**: Network and security configuration settings **SR 7.7**: Least functionality
ISA 62443-4-2	**CR 7.6**: Network and security configuration settings **CR 7.7**: Least functionality
ISA 62443-4-1	**SD-4**: Secure design best practices **SI-1**: Security implementation review **SVV-1:** Security requirements testing

15. Define a safe process state in case of a PLC restart

Define safe states for the process in case of PLC restarts (e.g., energize contacts, de-energize, keep previous state).

Security Objective	Target Group
Resilience	Product Supplier Integration / Maintenance Service Provider

Guidance

If something commands a PLC to restart in the middle of a working process, we should expect the program to pick up smoothly with minimal disruption to the process. Make sure that the process it controls is restart-safe.

If it is not practical to configure the PLC to restart-safely, be sure that it alerts you to this fact and that it does not issue any new commands. Also, for that case, ensure that the Standard Operating Procedures (SOP) have very clear instructions for setting the manual controls so that the PLC will start up the process properly.

Also, document all start-up, shut-down, steady state control, and flying control system restart procedures.

Example

/

Why?

Beneficial for…?	Why?
Security	**Eliminates potential unexpected behavior:** The most basic attack vector for a PLC is to force it to crash and / or restart. For many PLCs, it is not that hard to do, because many PLCs cannot cope well with unexpected inputs or too much traffic. While there are several diagnostics for controller actions while it is running, how it handles startup up with a running process is usually not clear. This may be uncommon, but it is a basic attack vector if we take into account malicious behavior of an attacker.
Reliability	**Avoid unexpected delays:** If after a PLC power on, the state machine initializes to a state with some conditions that don't let the process to start, and the operator cannot normalize the system, a technician would need to enter the PLC program to force the conditions to go to the desired state to be able to start operation. This could cause delays and production losses.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic**: TA009 - Inhibit Response Function **Technique:** T0816 - Device Restart/Shutdown
ISA 62443-3-3	**SR 3.6**: Deterministic Output
ISA 62443-4-2	**CR 3.6**: Deterministic Output
ISA 62443-4-1	**SVV-1**: Security requirements testing

16. Summarize PLC cycle times and trend them on the HMI

Summarize PLC cycle time every 2-3 seconds and report to HMI for visualization on a graph.

Security Objective	Target Group
Monitoring	Integration / Maintenance Service Provider

Guidance

Cycle times are usually system variables in a PLC and can be used for summarizing in PLC code. Summarization should be done to calculate average, peak, and minimum cycle times. The HMI should trend these values and alert if there are significant changes.

The cycle time is the time it takes to compute each iteration of logic for the PLC. The iterations are the combination of Ladder Diagrams (LD), Function Block Diagrams (FBD), Instruction List (IL), and Structured Text (ST). These logic components may be joined together with the Sequential Function Charts (SFC).

Cycle times should be constant on a PLC unless there are changes to e.g.

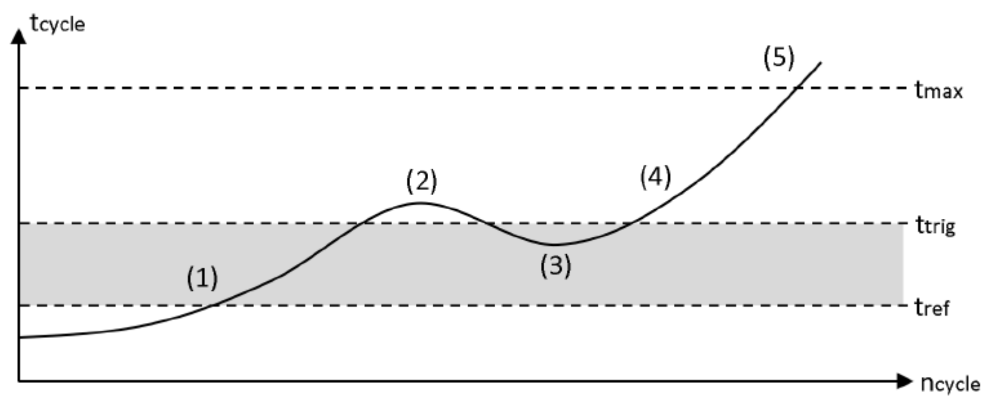
- network environment
- PLC logic
- process

Therefore, unusual cycle time changes can be an indicator that PLC logic changed and thus provide valuable information for integrity checks.

Visualizing values over time using a graph provides an intuitive way to draw attention to anomalies which would be harder to notice by just having absolute values.

Example

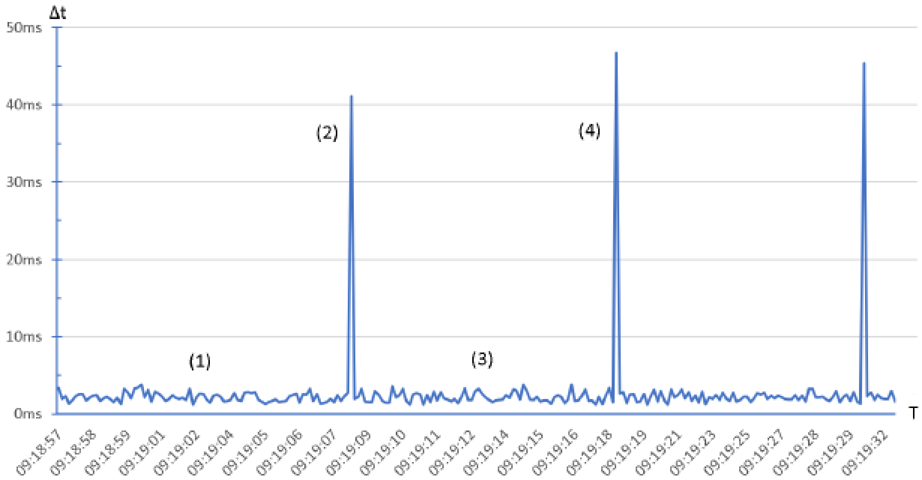
Many PLCs have a “maximum cycle time” monitoring at hardware level. If the cycle time exceeds the maximum value, the hardware sets the CPU to STOP (5).
Of course, attackers are aware of this and will keep a possible attack code as lean as possible to minimize the impact on the overall cycle time. In an additional software cycle time monitoring program, a reference cylce time tref is defined as base cycle time. As small fluctuations are natural, an acceptable threshold needs to be defined (1,3) The cycle monitoring is triggered, if the threshold is exceeded (2,4).



Any deviance from the reference time can be stored in a logfile like this:

SeqNo	Date	UTC Time	Abweichung
1	2019-11-22	09:05:50.021	40,821ms
2	2019-11-22	09:06:00.069	44,391ms
3	2019-11-22	09:06:10.120	44,994ms
4	2019-11-22	09:06:20.166	40,561ms
5	2019-11-22	09:06:30.211	40,725ms

If cycle times are trended to the HMI, heavy CPU loads are visible at a glance. The following example diagram shows an PLC-Program with periodically executed malicious code. (1,3) show acceptable cycle time fluctuations (“noise”) during normal operation, attack code is executed on (2,4) which increase the cycle time.



Why?

Beneficial for…?	Why?
Security	Attacks to PLCs include changing its logic, activating a new program, testing new code, loading a new process recipe, inserting auxiliary logic to send messages or activate some feature. For most PLCs, traditional cryptographic integrity checks are not feasible. However, it’s good to alert if any of the above logic changes happen. Since cycle times are rather constant under normal circumstances, changes in cycle times are a good indicator that the logic in one of the above logic components has changed.
Reliability	See security, but for non-malicious causes.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic**: TA002 - Execution **Technique:** T0873 - Project File Infection
ISA 62443-3-3	**SR 3.4**: Software and information integrity
ISA 62443-4-2	**EDR 3.2**: Protection from malicious code
MITRE CWE	**CWE-754:** Improper Check for Unusual or Exceptional Conditions

17. Log PLC uptime and trend it on the HMI

Log PLC uptime to know when it's been restarted. Trend and log uptime on the HMI for diagnostics.

Security Objective	Target Group
Monitoring	Integration / Maintenance Service Provider

Guidance

Keep track of PLC uptime

- in the PLC itself (if uptime is a system variable in the PLC)
- in the PLC itself if it has MIB-2 / any SNMP implementation
- externally by means of e.g., SNMP

If the PLC has SNMP with MIB-2, which is very common, the OID for uptime “sysUpTimeInstance(0)” is `1.3.6.1.2.1.1.3`. Uptime resets are important indicators for PLC restarts. Make sure the HMI alerts to any sort of PLC restart.

Uptime correlated with error codes are good diagnostics.

Example

/

Why?

Beneficial for...?	Why?
Security	The most basic attack vector for a PLC is to force it to crash and / or restart. For many PLCs, it is not that hard to do, because many PLCs cannot cope well with unexpected inputs or too much traffic. Thus, unexpected restarts can be an indicator that the PLC encounters unusual actions.
Reliability	PLC restarts are also good for diagnostics in case of failures and for monitoring which PLCs are being worked on at what time.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic**: TA009 - Inhibit Response Function **Technique:** T0816 - Device Restart/Shutdown
ISA 62443-3-3	**SR 7.6**: Network and security configuration settings
ISA 62443-4-2	**CR 7.6**: Network and security configuration settings
MITRE CWE	**CWE-778:** Insufficient Logging

18. Log PLC hard stops and trend them on the HMI

Store PLC hard stop events from faults or shutdowns for retrieval by HMI alarm systems to consult before PLC restarts. Time sync for more accurate data.

Security Objective	Target Group
Monitoring	Integration / Maintenance Service Provider

Guidance

Fault events indicate why a PLC shut down so that the issue can be addressed before a restart.

Some PLCs may have error codes from the last case where the PLC faulted or shut down improperly. Record those errors and then clear them. It might be a good idea to report those errors to the HMI as informational data or perhaps to a syslog server, if those features and that infrastructure exist.

Most PLCs also have some kind of first scan feature that generates events. It is a behavior that nearly all PLC equipment have in some form. It is basically one or more flags, or a designated routine that is executed on the first scan of a PLC after it "wakes up." This First Scan should be logged and tracked.

Example

/

Why?

Beneficial for…?	Why?
Security	Logs enable troubleshooting in case of an incident. Before a PLC becomes operational, especially after having experienced problems, it is important to ensure it is trustworthy.
Reliability	Logs are also good sources for debugging if the event was not caused maliciously.
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic**: TA009 - Inhibit Response Function **Technique:** T0816 - Device Restart/Shutdown 1
ISA 62443-3-3	**SR 7.6**: Network and security configuration settings
ISA 62443-4-2	**CR 7.6**: Network and security configuration settings
MITRE CWE	**CWE-778:** Insufficient Logging

19. Monitor PLC memory usage and trend it on the HMI

Measure and provide a baseline for memory usage for every controller deployed in the production environment and trend it on the HMI.

Security Objective	Target Group
Monitoring	Integration / Maintenance Service Provider Asset Owner

Guidance

Since the increase of lines of code in the logic can also lead to increased memory consumption at runtime, it is recommended for PLC programmers to track any deviation from the baseline and dedicate an alarm class to this event.

Example

In Rockwell Allen Bradley PLCs, a baseline can be established on a controller and memory usage can be tracked using the RSLogix 5000 Task Monitor Tool. Not only the main memory but also the I/O memory and Ladder/Tag memory can be tracked using trends.

Why?

Beneficial for…?	Why?
Security	Increased memory usage can be an indicator of the PLC running altered code.
Reliability	Tracking memory usage for the running programs could be useful in avoiding total memory consumption and eventual fault state for the PLC controller.
Maintenance	Tracking memory usage could be used in tuning and finding the best scan time for the monitored controller but also in troubleshooting problems and issues related to faulty states.

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic**: TA002 - Execution **Technique:** T0873 - Project File Infection
ISA 62443-3-3	**SR 3.4**: Software and information integrity
ISA 62443-4-2	**EDR 3.2**: Protection from malicious code

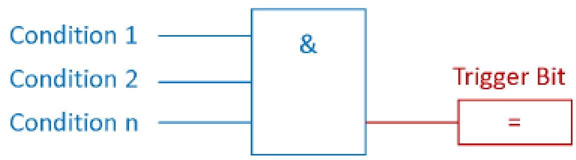
20. Trap false negatives and false positives for critical alerts

Identify critical alerts and program a trap for those alerts. Set the trap to monitor the trigger conditions and the alert state for any deviation.

Security Objective	Target Group
Monitoring	Integration / Maintenance Service Provider

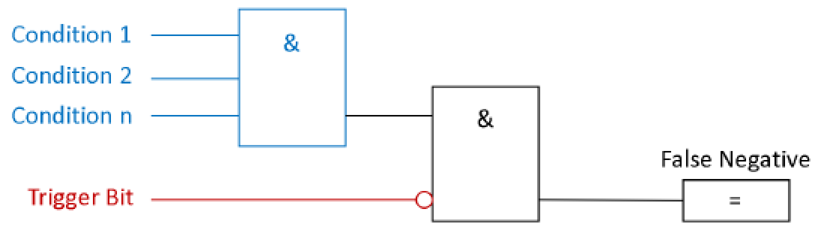
Guidance

In most cases, alert-states are boolean (True, False) and triggered by certain conditions as displayed below. E.g., the trigger bit for the alert 'overpressure' becomes TRUE, if Condition 1 'pressure switch 1', Condition 2 'pressure sensor value over critical threshold', through n., are TRUE.



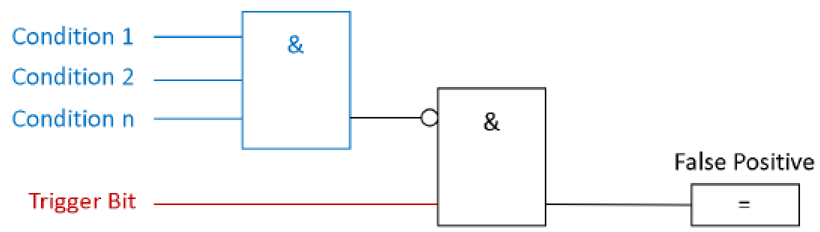
To masquerade an attack, an adversary could suppress the alert trigger bit and cause a false negative.

A trap for false negatives monitors the conditions for the trigger bit and the negated trigger bit itself. With this simple setup, a false negative is detected. See the following picture:



In other cases, an adversary could deliberately cause false positives, to wear down the process operator's attention.

In the same manner of the false negative trap, false positives can also be detected by monitoring the alert trigger bit and if the trigger conditions are met. If the conditions are NOT met, but the trigger bit is active, a false positive is detected: See the following picture:



Example

Example 1: Siemens offers in their Siemens S7-1200/1500 Products a Webserver with a wide range of functions, for example display of the PLC-State, cycle time or scope records. It also has the option to view and modify data tables and variables. The access rights to the Webserver can be modified in the PLC-Hardware Settings. In case of mis-configured access rights an adversary could gain access to the PLC Variables and Datablocks. To create a false positive, the adversary selects an alert trigger bit and alters the state.

Example 2: In the Triton/Trisys/HatMan attack, rogue code suppressed alert states.

Example 3: A bus-injection attack could send a false positive alert to a high-level SCADA client.

Why?

Beneficial for…?	Why?
Security	Mitigates false negative or false positives of critical alert messages caused by an adversary obfuscating their attack (i.e., rogue code, bus injection, tampering with accessible PLC state tables on unsecured webservers).
Reliability	/
Maintenance	/

References

Standard / framework	Mapping
MITRE ATT&CK ICS	**Tactic** : TA009 - Inhibit Response Function **Technique:** T0878 - Alarm Suppression
ISA 62443-3-3	**SR 3.5** : Input Validation
ISA 62443-4-2	**CR 3.5** : Input Validation
ISA 62443-4-1	**SI-1** : Security implementation review
MITRE CWE	**CWE-754:** Improper Check for Unusual or Exceptional Conditions

About the Secure PLC Programming project

For many years, Programmable Logic Controllers (PLCs) have been insecure by design. Several years into customizing and applying best practices from IT gave rise to secure protocols, encrypted communications, network segmentation etc. However, to date, there has not been a focus on using the characteristic features in PLCs (or SCADA/DCS) for security, or how to program PLCs with security in mind. This project – inspired by the existing Secure Coding Practices for IT – fills that gap.

Who should read and implement the Secure PLC Coding Practices?

These practices have been written for engineers. The aim of this project is to provide guidelines to engineers that are creating software (ladder logic, function charts etc.) to help improve the security posture of Industrial Control Systems. These practices leverage natively available functionality in the PLC/DCS. Little to no additional software tools or hardware is needed to implement these practices. They can all be fit into the normal PLC programming and operating workflow. More than security expertise, good knowledge of the PLCs to be protected, their logic, and the underlying process is needed for implementing these practices.

What is the scope if this list / how do you define PLC Coding?

To fit the scope of the Top 20 Secure PLC Coding practices list, practices need to involve changes made directly to a PLC. What you see in this document is a Top 20 selection of a larger number of potential secure PLC coding practices. There are also additional draft practices pertaining to the overall architecture, HMIs, or documentation. Those do not fit the scope of secure PLC coding, but could be on a future list on secure PLC environment.

What are the benefits of applying Secure PLC Coding Practices?

Using these practices clearly has security benefits – mostly either reducing the attack surface or enabling faster troubleshooting if a security incident were to happen. However, many practices have additional benefits beyond security. Some also make the PLC code more reliable, easier to debug and maintain, easier to communicate, and possibly also leaner. Further, the secure PLC coding practices not only help users in the event of a malicious attacker but also make the PLC code more robust to withstand accidental misconfiguration or human error.

Who’s behind this project?

It all started with Jake Brodsky’s S4x20 talk “Secure Coding Practices for PLC’s”.

After the conference, Dale Peterson initiated the Top 20 project. Jake Brodsky and Sarah Fluchs spent several hours on the phone to bring Jake’s proposed secure PLC coding practices to paper. Afterwards Dale, Jake and Sarah set up a platform at top20.isa.org, supported by ISA GCA, to structure and gather additional input from the ICS security and engineers’ communities.

Discussions and consolidation of the practice texts, and curating a list of the most relevant Top 20 practices took about a year; the process was accelerated by Vivek Ponnada who besides contributing and reviewing content, also organized regular calls until all comments on practices were resolved, Mohamed Abdelmoez Sakesli who added all the standards references in one big effort, the MITRE CWE team who provided the CWE references last-minute, Sarah who compiled the document you are reading now, and Jake, Dale, John Cusimano, Dirk Rotermund, Josh Ruff, Thomas Rabenstein, Gus Serino, Walter Speth, Agustin Valencia Gil-Ortega, Marcel Rick-Cen, and Al Ratheesh R, who provided input throughout the regular calls.

Supporters' list

The Secure PLC Coding Project is, and continues to be, a true community effort, which would not have been possible without countless contributors generously sharing their time and PLC/security knowledge. A total of 943 Users registered on the platform to discuss and contribute. Here is an alphabetical list of all who explicitly agreed to be named. Thank you everyone who took the time to support this project!

Aagam Shah
Adam Paturej
Agustin Valencia Gil-Ortega
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Andreas Falk
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Carlos Olave
Chris van den Hooven
Chris Sistrunk
Christos Alexopoulos
Cris DeWitt
Dale Peterson
Dene Yandle
Dennis Verschoor
Dirk Rotermund
Edorta Echave García
Gananand Kini
George Alex Holburn
Gus Serino

Josie Houghton
Jozef Sulwinski
Juan Pablo Angel Espejo
Khalid Ansari
Marc Weber
Marcel Rick-Cen
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Massimiliano Zonta
Matthew Loong
Matthias Müller
Michael Thompson
Michal Stepien
Miguel Angel Frias
Mohamed Abdelmoez Sakesli
Moon Eluvangal Chandran
Nahuel Iglesias
Nalini Kanth
Narasimha S. Himakuntala
Omar Morando
Oscar J. Delgado-Melo
Päivi Brunou
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Hakija Agic
Hector Medrano
Heiko Rudolph
Isiah Jones
Jacob Brodsky
Javier Perez Quezada
J-D Bamford
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Rick Booij
Robert Albach
Rushi Purohit
Sarah Fluchs
Sergei Biberdorf
Stephan Beirer
Steve Christey Coley
Thomas Rabenstein
Tim Gale
Vivek Ponnada
Vytautas Butrimas
Walter Speth

Special thanks to these organizations who generously provided infrastructure to use for the project team like domains, hosting, and web design and graphic design:

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