Secure Calibration in High-Assurance IoT: Traceability for Safety Resilience

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Abstract—**Traceable sensor calibration constitutes a foundational step that underpins operational safety in the Industrial Internet of Things. Traceability is the property that ensures reliability of sensed data by ensuring sensor accuracy is within a small error margin of a highly-accurate reference sensor. This is typically achieved via a calibration infrastructure involving a long chain of reference-calibration devices between the master reference and the IoT sensor. While much attention has been given to IoT security such as the use of TLS to secure sensed data, little thought has been given to securing the calibration infrastructure itself. Currently traceability is achieved via manual verification using paper-based datasheets which is both time consuming and insecure. For instance, when the calibration status of parent devices is revoked as mistakes or mischance is detected, calibrated devices are not updated until the next calibration cycle, leaving much of the calibration parameters invalid. Aside from error, any party within the calibration infrastructure can maliciously introduce errors since the current paper based system lacks authentication as well as non-repudiation. In this paper, we propose a novel resilient architecture for calibration infrastructure, where the calibration status of sensor elements can be verified on-the-fly to the root of trust preserving the properties of authentication and non-repudiation. We propose an implementation based on smart contracts on the Ethereum network. Our evaluation shows that Ethereum is likely to address the protection requirements of traceable measurements.**

I. Introduction

Connected robots are increasingly transforming a wide range of application areas, including but not limited to surgical suites [1] and industrial processing plants [2]. The use of automation in these areas brings forth the potential to increase the efficiency of output, yet accuracy and precision under adversarial pressure remains a constant worry. In the context of surgical robotics, for example, a high degree of accuracy and precision must be maintained as accurate sensing could mean the difference between life and death.

While a household IoT-alarm system typically requires calibration at manufacturing time alone, a high-assurance device such as a surgical robot needs much more. A calibration infrastructure distributed across the OEM, several third-party calibration agencies and suppliers involved in the supply chain are part of the calibration work-flow. The root of trust (calibration integrity) is a National Measurement Institute (NMI) that maintains the gold standards for sensing and measurment. This is typically a government agency such as the National Physical Laboratory (NPL) in UK or the NIST in USA. The root of trust for each type of sensor, consists of a master calibration device which is used to calibrated other calibration units that serve as a proxy for the master, and are in turn used to keep calibration units closer to the field calibrated. The field devices (such as the deployed robot) are calibrated using the calibration units at the bottom of the hierarchy, these are typically portable versions of the master-proxy carried by calibration engineers working for a third-party calibration agency.

As we start to rely on connected robots to perform critical tasks, we will start to see at least three changes. First, the security of the calibration infrastructure itself will start gaining importance and mechanisms will be required to deal with the obvious risks of fake calibration-engineers and calibration devices.

Second, calibration correctness becomes a safety-critical requirement. This means end-to-end measurement and calibration traceability at all times to ensure minimisation of calibration errors and associated liabilities. Ensuring correctness of calibration in the face of malicious actors, is crucial to address the operational resilience requirements of connected systems. We argue that the way ahead, is to ensure that all sensed data is subject to verification via *on-the-fly traceability checks*. This notion involves tracing sensed measurements to the corresponding gold standard, by involving all stakeholders: from the operator (e.g. surgeon in a hospital), to the manufacturer and their suppliers.

Third, how can the operator, regulator, manufacturer, and calibration agencies work together to create a tamper-resistant trail of recorded activity to aid system forensics, which can withstand hostile scrutiny in a court of law when things go wrong? There have been cases of lawsuits filed by patients, accusing hospitals of negligence over safety considerations when surgical robots have inflicted accidental injuries, and such are illustrative of the significant liabilities and stakes involved when ensuring robot safety.

II. Background

To ensure measuring instruments provide high quality and accurate measurements, we must ensure that they are calibrated against a trustworthy source. All measurements have a quantifiable degree of uncertainty and the challenge is to ensure that we can minimise this uncertainty, while maintaining a quantifiable indication of the quality of measurement. National standards for weights and measures are maintained by National Measurement Institutes (NMIs), such as the National Physical Laboratory (NPL) in the United Kingdom. NMIs define national measurement standards, which are associated with values of uncertainty and are used to calibrate measuring instruments.

The calibration of measuring instruments ensures that recorded measurements are of high quality and accuracy, such that they are compared to a standard of higher accuracy to identify errors in instrument readings. We calibrate to meet quality audit requirements and ensure reference designs, subsystems and integrated systems perform as intended. A reliable measurement should be recorded by instruments with low measurement uncertainty and is traceable to corresponding SI units, to a standard or reference method [3]. Traceability is at the heart of measurements and is a basis for comparisons against valid measurements. A measurement's metrological traceability is its property, such that the measurement result is related to a stated reference, through an unbroken chain of calibrations [4]. Shown in Figure 1 are paths in a traceability chain. As demonstrated by the diagram, each piece of end user equipment, hereafter referred to as an end node, can be traced back along the path to intermediary measurement facilities and ultimately to NMIs — which refer to the SI units as the basis for calibration. Each node in a path, being a NMI or intermediary facility, can branch out to other intermediary or end nodes, such that each piece of equipment can be used to calibrate a number of others.

Kaarls and Quinn state that a set of defined standard, or reference, methods can be created such that primary method(s) are used to validate or calibrate secondary or tertiary methods, which can be linked to a working-level method [5]. The use of primary methods are often time consuming and costly. A trade-off for typical working-level methods induce simplicity, but increases uncertainty. de Castro et Al. state the measurement uncertainty is an operationally defined method of detailing the level of confidence associated with a measurement [3], offering advantages over other terms such as precision and trueness.

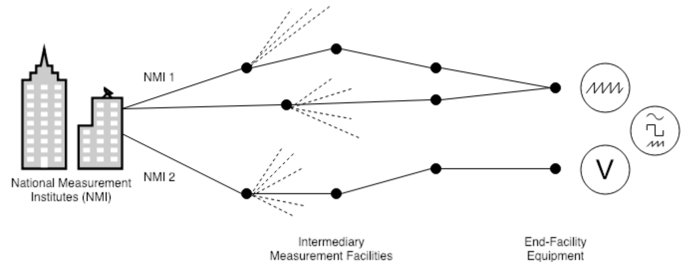


Fig. 1: Traceability Chain Paths

III. Protection requirements

Having noted that record-keeping around the calibration process is a foundational challenge to high-assurance IoT systems, several questions arise. What new security problems and what protection opportunities arise where the typical factory may have upwards of a 100,000 sensors, and thousands of such factories or labs share a few hundred calibration facilities. Clearly a future calibration framework will have to ensure good separation between rivals while also supporting dependable shared channels to ensure traceability chains back to a root calibration unit. If some of the calibration units are left on client facilities then are themselves susceptible to occasional compromise.

Current calibration assumes that all actors will behave themselves are thought to require little security. However just like early security protocols has to evolve under adversarial pressure, so too will calibration frameworks that have been traditionally thought to require little attention, have to change as we move towards the dynamic case — internet-connected devices that are compromised by malware and other attacks will require frequent and full resets of all prior state including calibration information. If the manufacturing facility comes under a targeted attack, engineers will have to design calibration frameworks that can deal with a stream of devices being added and compromised.

Scale is another important factor that designers must consider. As we move from the current deployment of networks involving a few connected sensors to larger networks with hundreds of thousands of sensors, we will need to assume that a fraction of the sensors will be compromised by insiders. Indeed the threat is no longer restricted to outside the facility.

We argue that the threat model must assume that the devices to be calibrated may be physically compromised, whilst being subjected to attacks arising from the combination of old software on newly-connected devices resulting in their software being tampered and therefore a fraction of the devices are rendered unsafe for use at any given point of time. Some calibration units especially those near the bottom of the hierarchy may also be compromised. The communication channels between various components of the calibration hierarchy will be subjected to the same attacks resulting in a fraction of compromised channels.

While the use of security techniques such as authentication and transport security are obvious, experience suggests that the likely challenges are going to be in key generation, distribution, update, and revocation. The foundational requirement is an authentication mechanism that establishes a rigourous mantle upon which the rest of the calibration record-keeping can be mounted. In addition to the authentication infrastructure, a resilient monitoring mechanism is a key requirement, which will alert operators and take steps to isolate rogue calibration units and end-devices.

The scale and complexity are significant. While conventional calibration techniques involve manual record keeping, a broad range of data can be monitored: we can query an instrument, other instruments in its vicinity, and their controllers; and we can also launch data plane probes to cross-check. With a large corpus of live and historical network data, the operator can make better decisions when under attack.

A. Threat model

The current verification process for calibration information has no associated threat model and thus to enable the need for digitisation, a sound threat model is the first step towards resilience. We believe there are at least four types of threats to the calibration infrastructure.

Large-scale compromise: First, an intentional attack by a state or state-sponsored group could discover systemic weaknesses that compromises a large fraction of the calibration infrastructure. These vulnerabilities could be exploited by a capable attacker resulting in seeding significant confusion in the best case. And, in the worst-case scenario, entire batches of a production-cycle might be compromised such as a whole batch of wrongly proportioned paracetamol landing up on a supermarket shelf.

Behavioural economics: Second, as the digital calibration infrastructure develops into hierarchical trees of substantial size with millions of participants, complex behaviours may arise as a result of system economics. For instance, selfish behaviours may manifest that optimises the costs of a fraction of the participant at the expense of the rest of the calibration ecosystem.

Flying debris: Third, secondary impacts of attacks directed at other targets may damage the calibration infrastructure. For example, a DoS attack may cause verification to fail if the network is shared with other systems leading. If verification is substantially delayed, it could make instruments uncontrollable triggering a precautionary shutdown.

Insider threat: Fourth, an insider may sabotage the calibration infrastructure. Although insiders are a persistent threat who may execute traditional physical attacks, cyber-security vulnerabilities give extra opportunities to damage assets.

B. Security policy

Following the threat model, the next step is to develop a security policy for the calibration system. A security policy is a succinct description of information flow constraints that stipulates the protection requirements to be met by security mechanisms, in order to mitigate the threats outlined in the threat model. Information flow controls are important. A move from the current peer-to-peer architecture underlying calibration devices and field instruments, any of which will cause havoc if compromised, can bring real benefits. The natural hierarchy within the calibration infrastructure when composed with information flow controls can compartmentalise risk, thus the compromise of a few units will do no more than local damage.

We argue that the appropriate information flow control for a calibration system is multi-level integrity, with root-calibration units calibrated by primary methods and references at the upper levels, field devices calibrated by secondary methods and references at the middle levels, and working level methods, references, and end-user equipment situated at the bottom. Also known as the BIBA model, this is similar to multi-level security systems typically used by government systems to enforce confidentiality by allowing information to flow from low-confidentiality to high-confidentiality levels (Eg. Top-secret to Secret to Confidential to Unclassified).

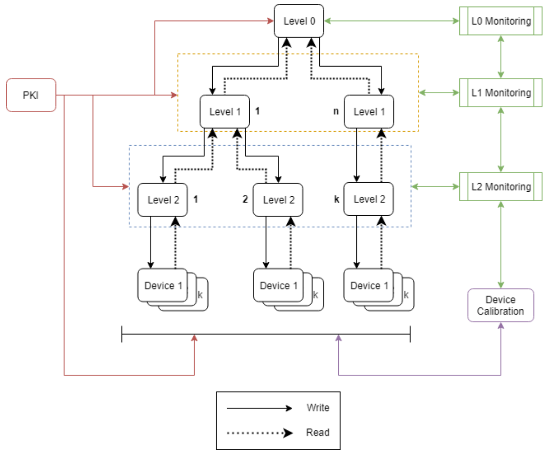


Fig. 2: Secure Calibration Architecture

The proposed security architecture for sensor and device calibration is as illustrated in Figure 2, has upper levels which consists of root-calibration units operated and managed by NMIs such as the National Physical Laboratory, each of which calibrate and manage the accuracy of tens of level 1 calibration devices, and each level 1 device in turn manages a few thousand level 2 calibration devices, each of which manage the calibration of tens of thousands of field level instruments. By coupling the calibration hierarchy with information-flow constraints, we can organise the measurement infrastructure so that only the compromise of top-level calibration devices can cause erroneous measurement at scale, thus reducing the number of critical components at least by a factor of hundred. Furthermore, with the use of appropriate controls at level 2, the compromise of a level 2 calibration device does little damage outside of its first-hop neighbours, then we can arrange to further reduce the sites of critical failure by another factor of ten. The calibration hierarchy can be readily extended, without much imagination, to map the hierarchical levels to local calibration components within a manufacturing environment.

We assume the root (level 0) and level 1 calibration devices can (rarely) suffer accidental configuration errors but are otherwise trustworthy. On the other hand, level 2 calibration devices may suffer occasional compromise and, as previously mentioned, a fraction of field instruments may be compromised at any one time which might misbehave, intentionally or otherwise.

C. Calibration levels and Measurement levels

We expect that most of the calibration work will be carried out by one or more middle levels consisting of mid-level calibration devices and calibrated field instruments that exist in the middle level. Level 1 and 2 organisations generally use master calibration units to calibrate other devices. This allows other calibration devices to be calibrated locally, reducing the time and cost for calibrating at level 0, as only the master unit needs to be sent to the level 0 organisation. Field devices are sent to level 1 and 2 organisations for calibration.

On the other hand, all the measurement work will be carried out by the field devices located at the bottom (leaf position) of the hierarchy.

Let them out, but not in: As previously described, any close-to-field calibration devices and field instruments may become a point of compromise at any one time, causing them to misbehave, intentionally or otherwise. A newly established network architecture, to define and constrain the behaviours — whether malicious or legitimate — of field instruments and close-to-field calibration devices, could invoke the use of refusing incoming connections and only allowing outgoing connections. Field instruments and close-to-field devices will be primarily used to transmit outgoing data and not receive incoming data.

Enforcing non-repudiation: As well as constraining the behaviour of field instruments and close-to-field devices, a discussion of mitigating possible compromise is necessary. An important point for mitigation is to ensure that instruments and devices are accountable for transmitted data, such as measurements field instruments may take and results from calibration units. The data should be recorded such that it can be traced back to the unit itself. This aids in the isolation of a device in the event of compromise.

Access granted: Across factory premises and different sites, what shared and private states are practical to hold and will any limitations be imposed as a result of state? A suitable access control policy should be defined such that calibration information can be made public by default, with organisations enabling an option to not publicly display this if they consider the information to be private. However, the discussion of privatising calibration information imposes a degree of difficulty on enabling the traceability of measurements associated with the privatised information. Therefore, to aid in reducing the difficulty of this process, the calibration framework could support an anonymised base system which also allows revocation. A set of scopes can be defined for the nodes in the traceability chain as shown in Figure 1, which determine the access constraints for data contained within the scope, whilst a general access policy can be used to cover data in a general scope.

D. Monitoring

Monitoring is a logical service in the network. The purpose of monitoring is to collect statistics from both calibration and measurement levels. Monitoring makes available its information to relevant users and operators so they can watch and intervene if needed. This service can perform both passive and active monitoring. Passively, it can measure statistics such as the number of measurements that match a certain pattern, the extent of traceability up the calibration hierarchy, or per-instrument error margins. Actively, it can interrogate a field instrument by sending a measurement request and observe the the instrument output. Monitoring also exposes a new level of control to the calibration infrastructure. The potential of using this for auditing and information flow analysis is immense. Among others, this makes available an interesting potential for tackling malware outbreaks as well as adapting and reacting to other forms of network attacks. The monitoring level also feeds data back into the measurement level.

E. Protection mechanism

To achieve the protection requirements described in the previous section, it is natural to consider the use of a blockchain as a solution. In accordance with our protection requirements for maintaining high integrity, the nature of a blockchain structure is ready to accomplish such. Through the use of strong cryptographic links among blocks, as well as a distributed network for storage and consensus, it would be extremely hard to tamper with or delete data from the blockchain. This not only aids in fulfilling our integrity requirement, but also enforces non-repudiation. Since the blockchain is a ledger keeping records of all transactions, we can ensure that devices cannot deny interactions or data production, and can thus be held accountable for their actions.

Although the blockchain is definitely impressive in terms of fulfilling our requirements thus far, we must consider what will be stored on the blockchain to aid with functions such as verifying the completeness of traceability chains in order to accept valid measurements, as well as providing a way to trace measurements back to field devices. From the calibration hierarchy, we know that all devices and units are associated with a calibration report, which outlines information about parent calibration units, operating ranges with a measurement uncertainty (MU), among other things. Figure 3 depicts an example calibration report. As well as this, the report will also detail the calibration technician who performed the calibration on the device or unit. Therefore, for completeness, storing reports as well as technicians on the chain is ideal. This will enable the contract to verify the calibration status of each device by looking up its associated parent unit(s), to trace upwards to the master calibration device (root) unit. The result is written to the chain, which enables the device user to check whether the device is calibrated against the root units that establish the gold standard. The use of ECDSA signatures prevents an adversary from forging calibration reports into the blockchain (explained in detail below). Also, to prevent the unauthorised use of valid calibration devices, the traceability-check contract verifies the signature of technicians all along the calibration hierarchy. A valid technician's signing keys must be signed by the calibration organisation's root signing key, and in turn signed by the NMI, which is the root of trust.

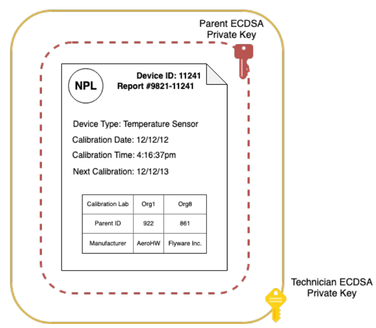


Fig. 3: Example Calibration Report

Considering the trace back to the calibration technician, we would also want to know what organisation certified the technician to perform calibration, and therefore we must also store the organisations in the calibration hierarchy, to allow for complete audit trails in the event of disaster which stems from invalid or improper calibration.

Now that we have established what will be stored on the chain, we must understand how we can use the blockchain for traceability verification checks. Popular implementations, such as Ethereum, use smart contracts to execute code and interact directly with the blockchain. To perform traceability verification, within a secure boot process (i.e. when the sensor starts up), we can use a smart contract. The smart contract will execute code that will verify whether or not there is a complete traceability chain, with each unit in the chain having valid calibration, before the sensor is allowed to start capturing data (Figure 4).

Algorithm 1 Trace Creation

```
procedure TRACECAL_WRITE(device_id)
    ▷ Get certifying organisation of device
    org_name = getCertifyingOrg(reports[
          TraceCal_READ(device_id)].device_id)
    if org_name == NPL then
        ▷ Set the trace to valid
        traces[device_id].device_id = device_id
        traces[device_id].trace_complete = true
        traces[device_id].valid_report = true
    else
        ▷ Trace is invalid
        traces[device_id].device_id = device_id
        traces[device_id].trace_complete = true
        traces[device_id].valid_report = false
    end if
end procedure
```

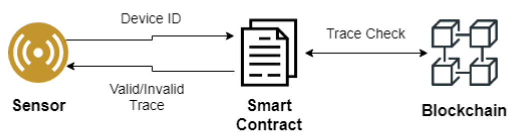


Fig. 4: Sensor Traceability Verification using a Smart Contract

Specifically, the contract will take the sensor's device ID as input to the smart contract, which will execute a function to verify it has complete traceability, as described in Algorithm 1. The algorithm will use another function to retrieve the root (calibration) report of the device's traceability chain, which retrieves the parent report from the chain, verifies signatures, and loops until there are no parents (Algorithm 2). It will then check the final device's certifying organisation to see if it is an NMI, in our case NPL, and if so, the traceability chain is valid and complete, and thus return a *verified* result to the device. Likewise, if there is no NMI root, the trace will complete but will return a non-verified result to the device. Furthermore, to retrieve a certificate itself, the smart contract will interact with the PKI system (depicted in Figure 2) to retrieve the certificate. In the algorithm, the signatures will be verified before accepting the parent identifier. The public key of the technician who calibrated the device is not that of the one who signed the parent, then the verification will fail and return a null result (ultimately resulting in invalid traceability), and otherwise will continue looping until the NMI root.

Algorithm 2 Trace Verification

```
procedure TRACECAL_READ(device_id)
    device_report = reports[device_id]
    parent_cert = certificates[device_report.parent_id]
    technician_cert = certificates[device_report.technician_id]
    ▷ If report is not signed by parent device, then fail
    if !(key_verify(device_report, parent_cert)) then
        return null
    end if
    ▷ If report is not signed by technician, then fail
    if !(key_verify(device_report, technician_cert) then
        return null
    end if
    org_cert = certificates[technician_cert.org_id]
    if verify_signature(technician_cert, org_cert) == false then
        return null
    end if
    if check_chain_of_trust(org_cert, ROOT_CERT) == false then
        return null
    end if
    ▷ Report now verified, now verify there is a root
    root_report_id = device_id
    parent = reports[root_report_id].parent_device
    ▷ Loop until there is no parent
    while bytes(parent).length > 0 do
        ▷ Verify parent report is signed by parent device
        if key_verify(parent,
          certificates[parent].parent_device) then
            if key_verify(parent, technician_cert) then
                root_report_id = parent
                parent = reports[root_report_id].parent_device
            else
                return null
            end if
        else
            return null
        end if
    end while
    return reports[root_report_id]
end procedure
```

Upon calibration, the device will be imprinted with a ECDSA public and private keypair, which are signed by the certified technician, establishing a chain of trust. The technician's keys used to sign the device's calibration report and are in turn signed by the organisation's keys who certified the technician (Figure 5), such that we can verify that the technicians themselves are not fake.

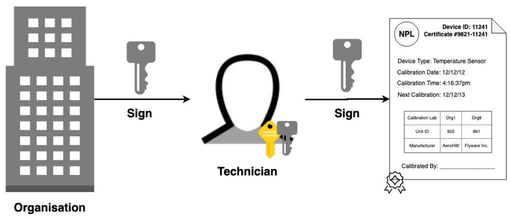


Fig. 5: Signing Calibration Certificates

Certified calibration organisations will be associated with their own keypair, which will be used to sign all calibration technician keys they wish to certify.

IV. Evaluation

In order to better understand the natural consideration of blockchains as a solution to fulfil our protection requirements, we must evaluate an implementation that can verify the completeness of traceability chains at any stage in the calibration hierarchy.

A. Blockchain Environment

For our blockchain implementation we used the Ethereum blockchain [6], a Turing-complete, decentralised *value-transfer* system which facilitates the use of smart contracts, written in Solidity, to interact with the blockchain. The programming language in Ethereum is implemented as a set of 140 opcodes which all nodes execute deterministically. The opcodes are condensed to form a bytecode string which can be published on the network, in the form of a smart contract. During deployment, a transaction is created by the account deploying the contract, and the contract is given its own unique address. When this transaction is accepted, the smart contract persists in the network. The contract may have various functions, and can also allocate persistent memory on the network. Any account which wants to interact with it uses the contract's address to call its various functions. The contract may contain two types of functions, including transactions and calls. Transactions are those which modify the persistent memory of the contract. They are called transactions specifically because they need to be run by all nodes to ensure synchronicity, and thus cost computational power. Calls merely read the persistent memory and can be run locally as well, and hence are free of cost. Since each transaction function requires computational resources based on the bytecode executed, there must be a way to charge each operation. Thus, every opcode is assigned a fixed cost which was tabulated when the network was deployed, and this cost is measured by units of gas.

1) Smart Contracts: The purpose of our smart contract is to define the functions of our protection mechanism, described in Section III-E, to interact with the blockchain to read and write data. In our smart contract, we defined functions for declaring aspects of the calibration hierarchy, as well as those for traceability verification. Specifically, we defined functions for creating and retrieving calibration organisations, certified calibration technicians and calibration reports, as well as creating traceability chains (traces) and verifying them. Table I describes the primary functions within our smart contract. Smart contracts are deployed and tested on private Ethereum blockchain (Ganache) as well as public Testnet (Ropsten Testnet) with the help of truffle testing framework.

2) Calibration Hierarchy and Traceability: To meet the definition of our protection mechanism, the smart contract should effectively be able to create the calibration hierarchy as well as provide methods to verify the metrological traceability of a given device or calibration unit. As previously described, we define functions to create calibration organisations and certified calibration technicians who will oversee and perform calibration of these devices, as well as providing two distinct functions: *TraceCal_WRITE* and *TraceCal_READ* to create and verify (read) traceability chains. These functions are described in detail in Algorithms 1 and 2, respectively.

3) Ropsten Test Network: In order to properly evaluate how our protection mechanism performs in a realistic environment, we deployed our implementation on the Ropsten test network [7]. Also known as the Ethereum Testnet, the Ropsten test network is the largest Ethereum test network and runs the same proof-of-work (PoW) protocol as Ethereum, but is designed for testing smart contracts before deploying them on the main Ethereum network. It uses a form of Ether, Ethereum's currency, called rEth which costs no real money. However, this can also be produced from Mining and can be received from faucets for testing transactions without imposing a legitimate cost.

In comparison with other Ethereum testnets such as Kovan [8] or Rinkeby [9], which use an alternative Proof-of-Authority (PoA) consensus protocol and have

Function	Description
createOrganisation	Accepts an ID and a name, and creates an organisation on the blockchain
createTechnician	Requests an Ethereum address and an organisation id, and will create a technician on the blockchain
createReport	Accepts a number of parameters, such as the device id and technician id, and creates a calibration-report object on the b
TraceCal_WRITE	Checks traceability for a specific device by checking if the technician who completed it is an NMI and writes the result
TraceCal_READ	Accepts a device ID and returns a root calibration-report if it has one, else returns the calibration-report of the device its
getParentReport	Accepts a device and returns its direct parent's calibration-report or NULL.
getOrgName	Accepts an organisation ID and returns the name of the organisation
getTechnicianOrganisation	Returns the organisation ID of the organisation who certified the technician

TABLE I: List of Implementation Functions

lower block confirmation times, the PoW Ropsten testnet best reproduces the current Ethereum production environment conditions and is useful for testing our protection mechanism against realistic transaction rates/times, number of nodes/miners, and gas prices, compared to those on the main Ethereum network.

B. Functionality Testing

The aim of our first set of experiments was to determine whether or not our protection mechanism functions as intended. Specifically, our functions to set up organisations, technicians and calibration-reports must properly create their respective objects, with the appropriate input parameters, and raise errors when these parameters are invalid.

1) Creating organisations, technicians and reports: When our smart contract is executed, we instantiate the calibration hierarchy with NPL as the root NMI organisation. From this, we tested creating organisations, with each certifying several technicians. These were created using the *createOrganisation* and *createTechnician* functions. These technicians would then go on to calibrate field devices and calibration units, which produces a calibration report upon completion of calibration; which ultimately need to be placed on the chain. To create a report, we use the *createReport* function in the smart contract. As expected, all our tests were successful, with the appropriate objects created on the chain. Appropriately, we also defined functions for data retrieval, such as *getTechnicianOrganisation* which gets the certifying organisation of a technician, for which all tests returned expected results.

2) Creating and verifying traces: Once we had confirmed that organisations, technicians and calibration reports were created and stored on the chain successfully, we developed functions for creating traceability chains, hereafter referred to as *traces*. For valid traces, a device or unit must have a series of antecedent parent units which ends at an NMI root, in our case NPL. The *TraceCal_WRITE()* function in our smart contract is used to check that there is a root report and that the certified technician who completed the trace is at the NMI root. The details of this algorithm are described in Algorithm 1. For devices that have a valid trace, the result should display that it has a valid calibration report, and invalid for those that do not have a valid trace. The result is then written to the chain, confirming that there is a valid/invalid trace corresponding to a particular device. Our unit tests for creating traces were successful in meeting our expected results.

C. Scalability Testing

For our next set of tests, we must evaluate how our protection mechanism scales with the ubiquitous nature and vast size of the calibration hierarchy. As well as this, we also evaluated how the addition of signatures, used for signing calibration reports (among others as described in Section III-E), affects how well our protection mechanism scales. The following tests which involve contract executing times have been run on a local blockchain using Ganache as the provider, and the Remix IDE to run the contract calls. We use Ganache to get the contract executing time as the contract is executed immediately, whereas on the main Ethereum network other contracts may be executed in the same block and measuring the execution time would be difficult. Likewise, we measured gas cost in the following experiments using the Ropsten network as Ganache provides an environment for testing contracts without costs, whereas Ropsten imposes gas and Ether costs like the main network but for free.

1) Impact of #Devices on Execution Time for Traces: For our first set of experiments, we measured the impact the number of devices in the calibration hierarchy has on the execution time of the smart contract for traceability verification. Firstly, to match the calibration hierarchy, we used varying numbers of field devices n as a baseline. From this, we deduce the number of levels as $log(n)$, such that if we have 100 field devices, the calibration hierarchy will consist of two levels as well as the root NMI. Furthermore, we map the number of organisations in the calibration hierarchy as $log_2(n-1)$, such that for 100 field devices there will be 4 organisations.

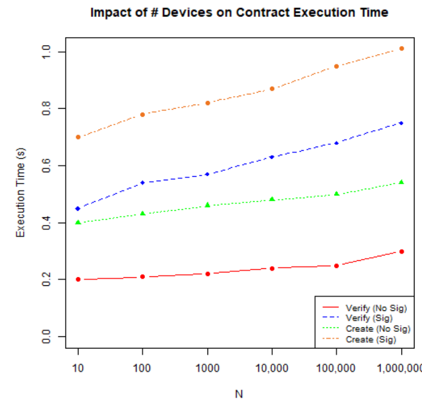
Next, we define the scope of our first set of experiments for n in the range $10 \leq n \leq 10^6$. As shown in Figure 6a, we observed the effect of n field devices on the contract execution time for creating (write) and verifying (read) traces. We observed that as the number of field devices and levels increase, the time for verifying traces increases. Similarly, the execution time for creating traces also increases with levels. In comparison with the verification times, creation times are at least 0.2 seconds more, as creating the traces involves retrieving the root calibration report and certificate, which our verification function uses as well.

Furthermore, we also observed the impact of adding signatures in our protection mechanism. For verification, the addition of signatures in the verification of traces more than doubles the contract execution time. Similarly, we also notice a similar increase in execution time for trace creation with signatures. Although this may seem a lot, if we consider the case of $1,000,000$ devices, the execution times are still only just over a single second. If we compare these times to what we would expect from the paper-based current state-of-the-art, they are an extremely significant improvement.

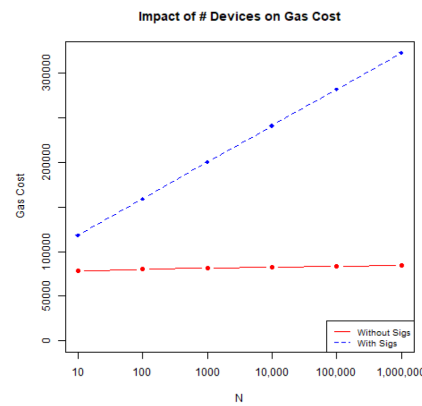
2) Impact of #Devices on Gas Cost for Traces: Using the Ethereum blockchain only imposes a gas cost when writing transactions and not reading from the blockchain. Based on this, it is interesting to observe how the imposed gas cost correlates with the number of devices (levels and organised further deduced from this). Observing the results from this experiment, depicted in Figure 6b, we can see that the gas cost increases linearly. However, this linear increase is relatively smaller in comparison to the increase in gas costs when we add signatures. Since gas costs correlate with the effort required to execute the smart contracts, our results suggest that the addition of signatures increase the effort required to execute the contract function.

In addition to gas costs, if we compare these results with those of the previous experiment, we observe that there is a correlation between execution time and gas cost. This relationship suggests that gas costs increases with contract execution time, and ultimately the amount of effort required to execute the contract.

As a point of further comparison, we also evaluated the contract execution times and gas consumed



(a) Impact of # Devices on Execution Time



(b) Impact of # Devices on Gas Cost

Fig. 6: Impact of # Devices on Execution Time and Gas Cost

for the other creation functions in our smart contract, specifically: *createOrganisation*, *createTechnician* and *createReport*. From the results in Table II, we can see that the completion time for these functions is relatively low compared to creating traces. This is because our trace creation function which includes looping antecedent levels of the hierarchy to reach the root, and verifying the calibration technician. With the addition of signatures, we notice that the completion time increases by roughly 0.3s in each case. Similarly with the creation of traces, the effort required to execute contracts with the addition of signatures increases, and thus the gas cost increases as well.

3) Impact of #Levels on Execution Time and Gas Cost: In our previous experiments, we derived the number of levels based on the number of field devices, n, as the primary variable. Realistically, there may be more than $log(n)$ levels, and it is interesting to evaluate how

Function	Completion Time (s)		Gas Consumed	
	No Sig	Sig	No Sig	Sig
createOrganisation()	0.5	0.84	87,282	172,890
createTechnician()	0.23	0.54	66,374	152,447
createReport()	0.43	0.80	114,095	293,771

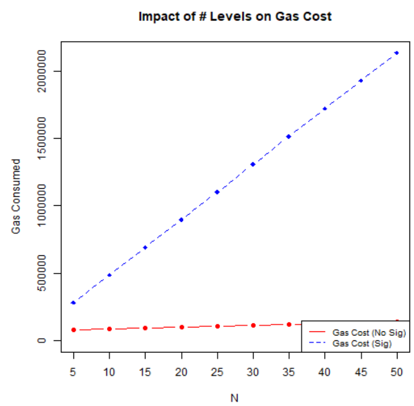
TABLE II: Completion Time and Gas Costs for Creation Functions

the number of levels impacts the execution time and gas cost. In this experiment, we measured the impact of the number of levels on execution times for creating and verifying traces, as well as the imposed gas cost on the creation of traces (as gas does not apply to reads). As shown in the results of this experiment in Figure 7a, the contract execution time increases in all cases as the number of levels increases. As both the creation and verification functions require reaching the root certificate, the time spent for both functions will increase as the number of antecedent units in a device's trace also increases.

Noticeably, the gas cost increases relatively linearly as shown in Figure 7b, which is similar to the results shown in Figure 6b, where an increasing number of devices also increases the gas consumed. Since the increase is linear, there is no significant impact on gas consumption due to the number of levels (nor devices). With the addition of signatures, the increase in gas cost is still linear, which shows that the number of levels still has no impact on gas cost, but the addition of signatures increases the effort required to execute the contract and such increases the gas cost. With respect to contract execution time, the addition of signatures seems to have little impact with a small number of levels, but increases significantly as the number of levels increase, taking around 7 seconds to create traces at 50 levels.

4) Impact of #Levels on Mining Time: Aside from the impact the number of levels has on increasing contract execution times and gas costs, it is interesting to consider the impact on mining time. When transactions are written, they are added to a list of recent transactions known as a block. This block will be added to the chain once verified by miners (proof of work), and thus there is a time for the miners to verify the transaction. Unlike using Ganache to measure the execution times, we used the Ropsten test network to measure the mining time. This is because there is no mining involved in the local Ganache Ethereum blockchain. As shown in Figure 8, the mining times fluctuate as we increase the number of levels with its lowest just under 20 seconds and near 140

(a) Impact of # Levels on Execution Time



(b) Impact of # Levels on Gas Cost

Fig. 7: Impact of # Levels on Execution Time and Gas Cost

seconds at its worst. This shows that there is no clear correlation between the number of levels and mining times, and thus we deduce that this factor is irrelevant to consider. Furthermore, due to there being no clear correlation, we did not find it reasonable to evaluate the impact of added signatures on mining time.

5) Impact of #Traces Per Day: For our final experiment, we wanted to calculate the gas usage per day, in the event of traces being crated multiple times. In our experiments, we noticed that the number of organisations did not have an impact on completion time or the gas cost imposed. Thus, if we had to run trace creations once an hour per day ($M = 24$), the time taken to complete the function should be consistent for one device at a particular level. The gas cost, however, will vary as it is measured as a quantity of runs. In our tests, we found that for level 3 devices $81,241$ units of gas were consumed, and for level 6 devices it costs $84,992$ units.

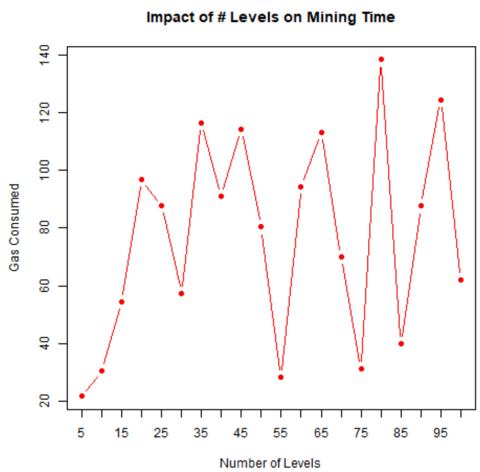


Fig. 8: Impact of Number of Levels on Mining Time for Trace Creation

Furthermore, with the addition of signatures, the gas costs increased by over $100,000$ units in both cases, with $200,126$ gas consumed for level 3 devices, and $322,942$ units consumed for level 6 devices.

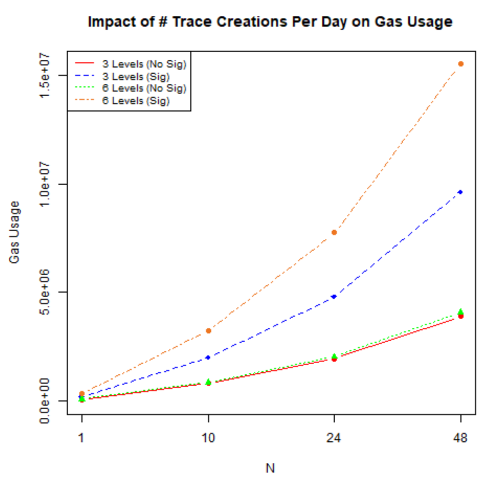


Fig. 9: Impact of Number of Trace Creations on Gas Usage Per Day

From these results, we experimented with the impact on the number of trace creations per day, on the gas consumed, for devices at level 3 and 6. As shown in Figure 9, we observed that the gas costs increase exponentially with the number of trace verifications per day. In the worst case of our tests, with 24 verifications per day (i.e. 1 per hour), roughly 15.5m gas units were consumed. Usually, we will perform a trace verification during secure boot and as such, only a small number of gas units are consumed. With the addition of signatures, we notice a larger exponential increase, but a relatively similar gas consumption at a single trace verification per day.

V. Discussion

As we start to use connected devices to perform critical tasks, such as performing surgical procedures on humans or other high assurance activities, ensuring that the system can operate safely whilst being robust to attacks is important. Additionally, we also require a strong tamper-resistant trail of recorded activity to enable system forensics that will withstand hostile scrutiny in a court of law. Indeed operational safety breakdowns resulting in injury to humans working alongside connected collaboration-robots (cobots) has been the subject of much litigation. These cases are illustrative of the significant liabilities involved and the stakes involved in ensuring safety within Industrial IoT settings. It is natural to pursue the development of safety assurance system that can provide data traceability, support decision forensics, and manage measurement uncertainty.

Our evaluation shows that the contract execution time for traceability verification has a linear increase in cost with the number of levels. Realistically though, the time required for contract execution will depend on the dynamics of miner availability and competing transactions. Further, the time required for the PoW scheme is two orders of magnitude (tens to hundreds of seconds) larger than the average verification time (a few hundred ms). As the most significant of all costs involved, mining time plays a crucial role given its variance. We note however, that this is primarily due to the widely acknowledged inefficiency of the PoW scheme used currently by Ethereum. In due course, it is expected that other mainstream blockchain technologies will be available, that utilise other consensus approaches that enable scaling of the mining process and with higher efficiency. We have therefore computed the time consumed for contract execution, separate from mining and block confirmation times, with emphasis on contract execution. Based on our scalability tests it is clear that contract execution scales rather well, and the inefficiency of mining is a significant barrier to the frequency of on-the-fly calibration checks that an IoT device can afford.

VI. Conclusion

An open challenge within industrial IoT processes is maintaining the integrity of calibration under adversarial pressure. Whilst there are many factors which contribute to this, including software patches to secure data storage, an important foundational requirement is to secure the calibration mechanism itself. In particular, the need for a mechanism that is: highly available, verifiable and tamper-resistant, for verifying traceability is becoming clear. While there is a natural hierarchy found in the calibration ecosystem, with a clear order of entities to which calibration and measurement information flows, it is unclear as how to best logically order actors in the connected world. In our research, we propose a mechanism that successfully establishes traceability chains, to ensure we can maintain valid calibration and rapidly attend to errors that may persist in high-assurance activities. Furthermore, we show that blockchains can provide a highly available tamper-resistant chain of evidence, which we can rely on in the event of catastrophe. Ultimately, we note that safety assurance relate to security, as much as managing stochastic interference, when we consider high assurance IoT to be connected.

VII. Acknowledgements

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