An Access Control Model for Robot Calibration

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ABSTRACT

High assurance surgical robotic systems require robustness to both safety issues and security issues (i.e adversarial interference). In this work, we argue that safety and security are not disjoint properties, but that security is a safety requirement. Surgical robotics presents new information flow requirements that includes multiple levels of confidentiality and integrity, as well as the need for compartmentation arising from conflicts of interest. We develop an information flow model that derives from lattice-based access control. This model addresses the flow constraints of the calibration lifecycle of surgical robots – an important aspect of a high-assurance environment.

1 INTRODUCTION

Modern robotics has transformed the way surgery is performed. Connected surgical robots, such as the DaVinci system, are increasingly playing a leading role in carrying out surgical procedures with human assistance. Instead of a surgeon wielding a scalpel, the robot carries out the core surgical procedures including performing the incisions, controlling blood loss, and carrying out repair work, under the oversight of human surgeons. Surgical robots promise lowered risks compared with traditional procedures – quicker surgeries, fewer complications, lowered blood loss and transfusion rates, and a shorter length of recovery for the patient.

As we start to use connected robots to perform critical tasks such as performing surgical procedures on humans, several challenges arise. First, how can we ensure that the system can operate safely whilst being robust to attacks. Second, how can one develop a strong tamper-resistant trail of recorded activity to enable system forensics that will withstand hostile scrutiny in a court of law. Indeed, in the last few years several lawsuits have been filed by patients accusing hospitals of negligence over safety considerations when surgical robots caused accidental injuries to patients whilst working deep inside their bodies. These cases are illustrative of the significant liabilities involved and the stakes involved in ensuring robotic safety. It is natural to ask about the implications of robot safety assurance on security in general, and for access control models in particular.

Safety assurance is going to be about security as much as managing stochastic interference. The security properties of interest in order of priority is system availability, followed by integrity rather than confidentiality. The importance of availability is well understood – it means ensuring that the services offered by the robot is available to the surgeon when expected. As such, other properties are of little consequence if the robot cannot do what it should.

When integrity is intact, it means that the robot has not been maliciously altered. To ensure robot integrity, several considerations are involved. First, calibration will no longer be a yearly affair, but a monthly one, with integrity checks in between that verify the traceability of calibration from the hospital to the manufacturer and their suppliers. Indeed, the liabilities of error reside not just with the hospital and the equipment supplier, but further along the supply chain as well. It isn't necessary that a device vulnerability will need to be exploited by a skilled attacker who has access to the patient's environment. Instead, malware controlled by a remote attacker can launch attacks. And, it will have to be fixed immediately rather than wait for the next patch to arrive. As such the safety capital will move from an upfront cost to a continuous cost and it will be hard to predict how much it will cost to fix, thus impacting the bottom-line. More importantly, calibration and other safety-assurance activities will move from a periodic or one-off activity to a safety need that must be maintained in real-time.

So what is the appropriate authorisation framework for calibration safety of surgical robots in hospitals? How can we ensure that calibration certificates are not forged or tampered with? How can we identify components that require calibration even though their certificates haven't expired? How will calibration-patches be applied, eg. a parent device that has been used to calibrate a component of the robot is subsequently found to have an issue, requiring a revocation or refreshing of all certificates down the calibration chain. How can we prevent fraudulent calibration devices (reference devices) from being used to calibrate a surgical robot? How can we enable transparency in the calibration traceability-chain whilst ensuring the confidentiality of who supplies to whom and who calibrates their devices? And finally, in aid of system forensics, how do we go about creating a tamper proof log of calibration, adjustment, verification, and robotic operation?

2 BACKGROUND

2.1 Surgical Robotics

Robotic surgery equipment, such as the da Vinci Surgical System [10], can provide medical professionals with robot-assistance for procedures to improve surgical performance.

The da Vinci robot is a *quadbrachial* (four-arm) robot, which are human-operated via a surgeon's console with finger controllers that transmit the human movements to the robot. One of the arms consists of a camera to give the operator a high-definition view of the surgery they are performing. As well as this, the console also has foot pedals which, when operated, control the camera and also procedures such as cautery. A dual-console may also be used, which allows for another surgeon to view the procedure, as well as takeover when relief is required. The video feed from the camera is also transmitted to screens in an observation room, which allows viewing of the surgery without being in the room. A digital router in the surgical system allows for recording cases and transmitting them to any monitor inside the room, as well as to the Internet using a transmission device such as Polycom HD [8]. Internet images from, for example, radiology suites can be transmitted to the router and ultimately to the surgeon console, providing real-time radiology images during the procedure.

According to [9], the da Vinci robot is composed of three components: a surgeon's console, three cart-mounted arms (one for the camera and two for instruments), and a vision cart. Similarly, the Zeus system also consists of three components, which include the console, a computer controller and three arms. On a large scale, we consider having tens of surgical robots in a single hospital, where each surgical robot would have a surgical console as well as a digital router to handle data inputs and outputs to other parts of the hospital and back-end systems. We can therefore suggest that the level of compromise is not limited to just one surgical robotics suite, but to multiple, and adversarial threats will not just be limited to a single operating theatre, but to many throughout the hospital. If in the event an adversary attempts to slow down a robots process(es), it could affect how the surgery is performed and may disrupt the surgery or result in patient deaths in the worst case. On a scale of tens of surgical suites, having multiple casualties would heavily affect the reputation of a hospital and would more than likely result in lawsuits, all of which can have a detrimental impact on a hospital's success.

The RAVEN II surgical robot [3] is a surgical robot which includes two mechanical arms which are used to operate two respective instruments. It is an experimental platform which contains the control and safety mechanisms which would be found in state-of-the-art surgical robots, and allows the robot to be teleoperated. An additional feature to the RAVEN II robot, is in-built safety mechanisms such as an emergency stop, which puts the robot and its control software into an emergency stop state, where a robot can only be taken out of this state when a physical start button is pressed. This allows the operator(s) of the robot to halt anything the robot is doing when faced with a hazardous event.

The da Vinci surgical system is a real-world implementation of a surgical robot, whereas the RAVEN II robot is an open-source platform used for research in surgical robotics. However, both of these surgical robots envelop a similar architecture which covers the majority of surgical robots in use to date. [1] details that the most critical component of surgical robots is its electronic control system, which both receives the commands from the surgeon's console and translates these into robotic actions, and provides video feedback to the surgeon's console.

An interesting observation is that the architecture of the surgical robotics systems we described, are the same as most industrial robots. Quarta et al. [6] provide an experimental security analysis of the architecture of industrial robots. In their evaluation, they used an industrial robot, from leading vendor ABB, that consists of the same architecture as the majority of industrial robots, and more specifically consists of the robot system paired with a controller than can be operated both by a human and autonomously. There is a main control system that links the components of the robot, the network in which it operates, and the controller together. As with surgical robots, in industrial robotics, the control system is regarded as one of the most safety- and security-critical components. Similar to the da Vinci system, the industrial robots have an internal robot network, where the components of the robot system communicate with eachother, as well as a service network where the robot is connected to a dedicated organisational subnet and possibly to the Internet.

2.2 Calibration

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 [2]. 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].

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 [2], offering advantages over other terms such as precision and trueness.

Surgical robots and their components are made at several manufacturing facilities, where each component is initially calibrated to some national standard. The calibration is performed by a human operator, who may be based in the equipment manufacturing facility, an intermediary calibration laboratory, and/or a top-level body known as a National Measurement Institute (NMIs) in metrology literature.

After calibration, the process is usually verified by another operator and then adjustments are performed if and where necessary. This invokes a second level of confidence in the calibration of equipment. With this said, operators may hold expertise and accreditation for calibration, but not all operators may be certified (i.e. end-users calibrating their own devices).

When a device is calibrated, it is issued with a calibration certificate. Most devices require recalibration after a specified time period, which is at yearly intervals. From this, we note that there are threats to the integrity of calibration certificates. For example, calibration certificates hold a timestamp of the calibration, calibration-specific data and the parent units that were used to calibrate the device. This opens up scenarios where attackers may forge calibration certificates, or modify the data within a calibration certificate. The

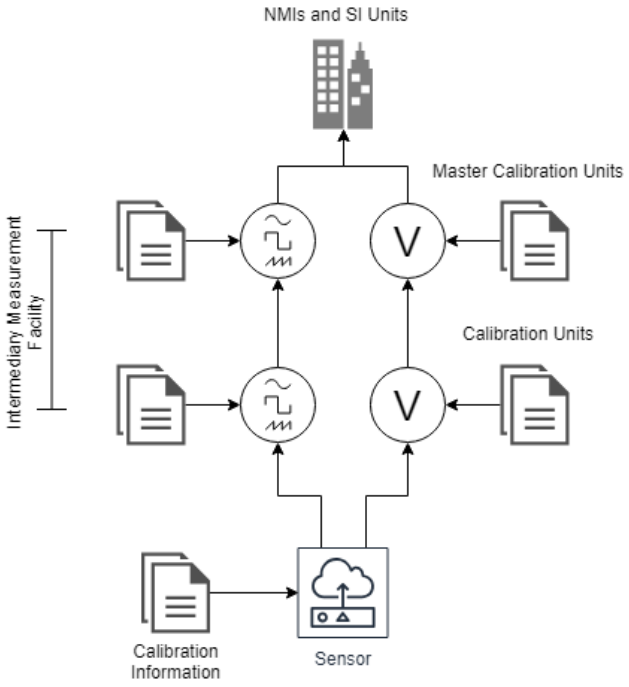

Figure 1: Calibration Hierarchy

attacker may add false calibration units to the certificate, and if high level operations such as traceability were carried out, it could reveal sensitive information to the attacker.

Some operators may also perform verification and adjustment using the same equipment as the original calibration. If the calibration units had a high uncertainty or were miscalibrated, it could result in inaccurate verification and/or adjustment, as well as the initial calibration.

3 ACCESS CONTROL FOR CALIBRATION

3.1 The Calibration-Safety Access Control Problem

Robot inspection and calibration, while necessary are not sufficient for achieving operational safety as the calibration involves a large number of parties, a fraction of which may act maliciously. In this paper, we are concerned with threats which relate to the calibration of surgical robots.

The primary approach for ensuring robot safety just before executing a surgical procedure, is to ensure that on-board sensory equipment satisfies calibration traceability. Traceability means verifying whether a measurement can be traced to a master device with low measurement uncertainty. The master device is typically a very expensive sensor (e.g. an atomic clock) with very low error and hence fit to define a measurement standard. In high-assurance applications, traceability is an important property. Instead of taking a calibration certificate at face value, the device operator also checks the validity of calibration certificates of parent devices used to calibrate a robot, and their parents, and so on until the root calibration device. Figure 1 shows how calibration information is verified by tracing calibration certificates through a chain of hierarchical domains.

To verify traceability, the operator needs access to genuine calibration certificates pertaining to all devices on the chain between the robot and the master calibration device. There is more to this than just checking certificate provenance. The operational range of each sensor component needs to be validated as well, in real time. As an example, consider the temperature sensor mounted on the da Vinci's needle driver, which ensures the needle tip does not heat up to a point that it causes burns when stitching up a wound – a build up of scar tissue can delay recovery especially in areas of primary repair. The sensor may be calibrated for operation from 12 to 60 Celsius and hence expected to report accurate values with low uncertainty in this range. However, this assumption is not confirmed unless the parent device used to calibrate the robot's sensor, was also calibrated for at least the same range, and similarly all the way up to the national standard. Also, at any point, the calibration certificate of a parent device could be revoked or modified. In our example, if the calibration certificate of the two-hop parent of the robot is found to exhibit high-uncertainty above 45 Celsius, then its calibration certificate should be revoked and replaced. The new certificate only permits the grand-parent to act as a calibration device up to 45 Celsius, whereas our robot already has a calibration certificate allowing operation up to the maximum safe temperature of 60 Celsius and is in the middle of a surgical procedure. If the robot continues the surgery it could be operating in unsafe conditions, and the resulting liabilities could be dumped on the operator.

The above example shows why maintaining safety is a requirement that must be met in real time — if a calibration patch is issued, it needs to be applied immediately (and restrict the needle to the maximum temperature that can be traced to national standards).

3.2 Access control model

To enable traceability and to apply calibration patches, an appropriate authorisation framework is essential.

To protect against information leakage and disclosure, such as who is calibrating who's devices, and how often the traceability chain is checked for integrity, we propose an information flow model that leverages existing notions of access control to manage the multiple levels of confidentiality, integrity, and conflicts of interest sets. The proposed hybrid model naturally builds on the BLP model, the BIBA model, and the Chinese Wall model.

3.2.1 Multi-level integrity. Fortunately, a calibration hierarchy naturally exists in the world of calibration. If we design the authorisation framework well, then we can reduce the number of critical components by an order of magnitude. To show how, a robot deployed in a hospital, as illustrated in Figure 2, has thousands of components (sensors and actuators) at the bottom most level, with every ten or so sensors calibrated by a level-2 units, every ten level-2 calibration units are in turn calibrated by one level-1 calibration unit. If we can ensure that the compromise of a level-1 unit or its signing keys can only cause limited damage by impacting components within its immediate locality, as opposed to widespread damage. Starting with the master calibration level, at each subsequent level, the number of critical components calibrated is reduced by one order of magnitude.

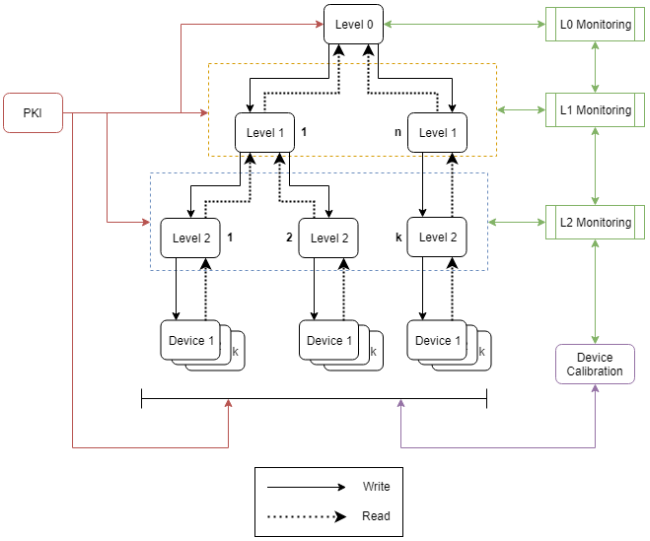

Figure 2: Calibration hierarchy with PKI and monitoring services

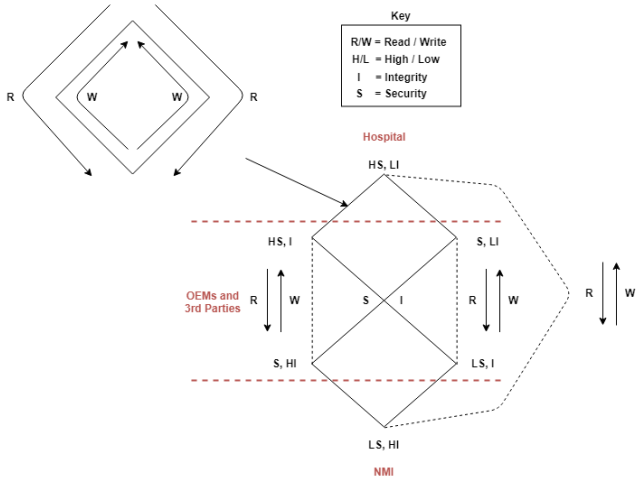

Figure 3: Access Control Model

It is plausible to map the components of the calibration hierarchy to real actors within the calibration chain without a lot of imagination. A component's calibration certificate could potentially reveal the facility at which the calibration was performed. In the case of NMIs, the information is globally available, and thus the mapping of the component to themselves does not succumb to any confidentiality concerns. However, in the case of intermediary facilities, who do not wish to reveal information to levels above and below them, a mapping of components becomes a concern. For example, the calibration certificates contain information about the calibration units used to calibrate the component being mapped, as well as measurements recorded throughout calibration. This would potentially leak confidential information about the actors performing the calibration, in this case the intermediary facility, as well as the internal calibration architecture and processes of the facility.

We assume that level-0 and level-1 calibration units will be trusted with a chance for error or misconfiguration. At level-2 there will be some chance of compromise, since these devices will come in contact with field devices. The calibration software running at level-1 and level-2 might be compromised or misbehave unintentionally. Some proportion of field components (devices and sensors) may be compromised at any time, and as the measurements drawn from such devices suffer from very high uncertainty, nothing can be assumed of them.

3.2.2 Multi-level confidentiality. The timing of integrity checks (traceability chain) could leak information about the timing of surgical procedures, thus potentially breaking patient confidentiality. For instance, when combined with other sources of information, such as the time of patient admission and exit and the calibration-traffic fingerprint, it may be possible to accurately estimate which patients will be served by a DaVinci robot and for what medical condition. Aside from timing and frequency of checks, the verification of a traceability chain should not reveal information about the deployment to intermediaries involved between the deployed robot and the public-facing national measurement institute. The reason for this is simple: calibration traffic from intermediaries could leak confidential information to parties further in the chain. As an example, a device manufacturer might use the services of a third party to calibrate the robot's sensors but does not want to reveal who this third party is. Thus an important requirement is that the traceability chain of the robot should be verifiable without leaking information about the hospital to the intermediate providers of calibration services, and likewise from the providers to the measurement standard bodies (National Measurement Institutes).

This motivates a multilevel security policy designed to protect confidentiality like BLP. We place the robotic device at the top level of highest confidentiality, as much of the meta information around calibration traffic is directly or indirectly linked to patient confidentiality and the hospital's operational confidentiality. This information cannot be leaked even to the providers of calibration services and the OEMs of surgical robotic equipment, who are one level below the hospital. So the OEM and calibration service providers can be consulted by the deployment to query traceability (read up) without allowing the providers to learn any information about the state of the surgical robot (no write down). Finally at the bottom most level, we place the National Measurement Institutes' master calibration devices who have no secrets to keep, but should not have access to any meta information about traceability chain verifications from the deployment site or calibration-service providers.

3.2.3 Chinese walls. Robots also require periodic recalibration. Here the concern is of unintended disclosure. A calibration engineer who works for a robot-maintenance company cannot be allowed to calibrate robots for competing companies. Indeed, calibration software and equipment belonging to a calibration engineer could contain embedded malware trojans which are deployed at one company. The calibration process could then be exploited as

an attack vector to transfer malware to competitors, leading to a situation where information disclosures occur between companies having a conflict of interest. In rare cases, a crooked calibration engineer might collect business sensitive information as derived from device logs and resell such information to competitors. Thus we have a set of companies including OEMs and third parties that provide calibration services to hospitals. These companies are in direct competition with each other and are thus *partitioned into conflict of interest sets*. Therefore, it is important to protect against the disclosure of sensitive information across companies.

3.3 Information flow model

In summary, we have a set of intermediaries (OEMs and third parties that provide calibration services to hospitals), all of whom have confidentiality requirements. The device is at the highest level of confidentiality while the NMI's information is public (unclassified). Simultaneously, we have measurement-integrity requirements which flow from the NMI (highest integrity) to the intermediaries on to the field-level surgical robots in hospitals (lowest integrity). While managing these confidentiality and integrity requirements, we need to further protect against hospitals and intermediaries who are in direct competition with each other. This means a hybrid access control model that builds on BLP, BIBA, and the Chinese wall model [7]. We now define terms used in subsequent discussion.

(Definition) Conflict-of-interest set is defined as the set of subsets where each subset corresponds to calibration-service providers in a direct conflict of interest with each other. Following standard notation, we denote the set of n conflict of interest sets as $\{COI_1, COI_2, \ldots, COI_n\}$. Each set $COI_i = \{1, 2, 3, \ldots, m_i\}$ contains the set of m_i providers that are in conflict.

(Definition) Set of integrity labels is denoted as $\Omega = \{\omega_1, \omega_2, \ldots, \omega_q\}$. Each integrity label corresponds to a unique integrity level.

(Definition) Security labels are defined as a set of two n-sized vectors $\{[i_i, i_2, \ldots, i_n], [p_i, p_2, \ldots, p_n]\}$, where $i_j \in \{COI_j \cup \perp \cup T\}$, $p_j \in \Omega$ and $1 \leq j \leq n$. $i_j = \perp$ signifies that the calibration traceability chain does not contain information from any provider in COI_j. $i_j = T$ means that the calibration traffic contains information from at least two providers who are in a conflict of interest set COI_j. $i_j \in COI_j$ means that the calibration traffic contains information from the corresponding service provider in COI_j. And, $p_j \in \Omega$ denotes the integrity component of the security label.

(Definition) Dominance relations: Next, we define dominance relations between the labels as follows, where the notation $l_j[i_k]$ denotes the i_k^{th} element of label l_j. We say that security label l_1 dominates label l_2 denoted by $l_1 \geq l_2$ iff. $\forall i_k, p_k = (1, 2, \ldots, n)[((l_1[i_k] = l_2[i_k]) \vee (l_2[i_k] = \perp) \vee (l_1[i_k] = T)) \wedge (l_1[p_k] \leq l_2[p_k])]$.

In other words, l_1 dominates l_2 provided that l_1 and l_2 agree whenever l_2 is not public or in conflict and the integrity level of l_2 is higher than that of l_1. Information flows in the opposite direction of dominance, if $l_1 > l_2$ then information can flow from level 2 to level 1 but not vice versa. The dominance relation is transitive. The public level corresponding to the National Measurement Institute outputs$\{[\perp, \perp, \ldots, \perp], [\omega_q]\}$, is dominated by all the other levels.

Similarly, system high is denoted by $\{[T, T, \ldots, T], [\omega_1]\}$, dominates all the other levels. Note that the dominance relation defines a lattice structure, where level public denoted by $\{[\perp, \perp, \ldots, \perp], [\omega_q]\}$ appears at the bottom and the level trusted appears at the top. Incomparable levels are not connected in this lattice structure.

Although we have both integrity and confidentiality requirements, these are complimentary. Our information flow model is an instance of Sandhu's observation that BIBA and BLP are the same model. This becomes true in our case as the level with the highest integrity (Master calibration reference) is also the level with the lowest confidentiality requirements, and likewise the level with the highest confidentiality (hospital) has the highest measurement uncertainty and thus the lowest integrity. This means that there is no contradiction between the information flow rules of BIBA and those of BLP. The rules for information flow as they apply to the hybrid model shown in Figure 3, are as follows:

(1) Simple property: A principal (S) may read a calibration certificate (O), only if $L(S) \geq L(O)$.
(2) Confinement within chinese walls: A calibration service provider (S) can only calibrate a device (O), if the security label of the device dominates that of the service provider i.e if $L(O) \geq L(S)$.

The notation style are based on the work of Sandhu [7].

4 CALIBRATION LIFECYCLE AND ACCESS CONTROL

Overall, we note there are three phases of the robot calibration life cycle: (1) initial calibration of a device, (2) recalibration after expiry of calibration certificates, and (3) authorising recalibration from other factors (e.g. upper-layer calibration units require recalibration).

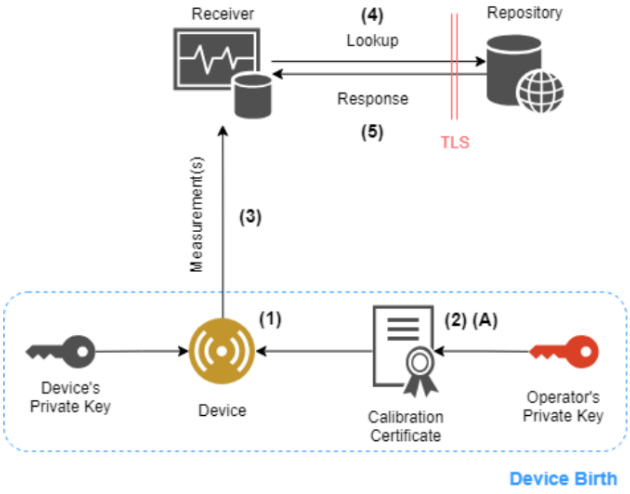

Figure 4: New Calibration Architecture

4.1 Initial Calibration

A device's initial calibration is the first step which outputs a calibration certificate, specific to the device, and becomes part of the traceability chain. Its initial calibration is primarily performed in two ways: by the device manufacturer in the manufacturing organisation's calibration facility, or by NMIs. Based on the notion that

the device is assigned to part of the traceability chain for the first time, we hereby refer to a device's initial calibration as the *birth* of the device.

In Figure 4, we identify what is required for the birth of a device into the calibration network, how measurements are sent securely to the receiver, how one can perform a lookup for the calibration certificate of a device and finally, how the information is stored.

4.1.1 Device Birth. The birth metaphor inspired by biology helps describe the behaviour which implements secure initialisation of the device by imprinting it with a key pair. This work is done at the one of the intermediate levels $\{[\bot, \bot, \ldots, OEM_i, \ldots, \bot][\omega_j]\}$ of confidentiality and integrity corresponding to the organisation OEM_i.

When a device is born, a public and private key pair, which we refer to as K^d_{pub} and K^d_{pri}, is embedded into the device firmware when it is inserted into a manufacturer or OEM's calibration station. This is the only time credentials can be imprinted. K^d_{pub} is then signed by the manufacturer's signing key K^M_{pri}. This creates a link between the manufacturer and the device, which can be used to verify device measurements by tracing them to high-integrity devices via the chain of calibration certificates – i.e the device's calibration status, and the calibration status of the parent device used for calibration, its grandparent, and so on up to the master calibration device.

A calibration operator (calibrator) then performs the calibration process. Calibration can only be performed by a calibrator if they don't have a conflict of interest with the device OEM i.e $L(OEM_i) \geq L(TP_j)$ where i is the index of the OEM and j is the index corresponding to the third party acting as calibration-service provider. The output of the calibration process is a calibration certificate with security label $\{[\bot, \bot, \ldots, OEM_i, \ldots, TP_j, \ldots, \bot][\omega_i]\}$. Since, the certificate contains information about the OEM manufacturing the device and the Third Party (TP) that carries out the calibration, the security label assigned lists the company names in the respective conflict of interest classes. As show in Table 1, the certificate contains information about its parent calibration units, the calibrator, and a measurement function $M : x \rightarrow y$, where y is the corrected output for a given measurement x produced by the device's sensor. Additionally, a timestamp field details the time at which the calibration certificate was produced, and the expiry field specifies the expiration time and date of the certificate, used to alert recalibration. The calibrator then signs the calibration certificate with their private key, to bind all the certificate elements together and link the device to the calibrator.

Transmitting Measurements. Once a device is born and ready to use in the field, it generates measurements signed with its private signing key K^d_{prv}. Measurements are unstructured pieces of data which may or may not be continuously streamed to the receiver.

4.1.2 Lookup for Calibration Certificates. As depicted in Figure 4, the subject requesting the calibration certificate for a device would send a lookup request to the OEM, i.e. OEM_i. The lookup request would succeed if the label of the requester dominated that of the certificate.

Calibration Certificate	
Device ID	
K^d_{pub}	
Timestamp	
Expiry	
DID_1 | DID_2 | … | DID_n	
Calibration Factor	92.4%
Voltage Reflection Coefficient	0.01
…	…

Table 1: Calibration certificate

Measurement ID	Device ID	Timestamp	Payload	$\odot K^d_{pri}$

Measurement Structure

4.2 Calibration Traceability Verification

After device birth, the manufacturer will hold the device until it is placed at its deployment site, such as the hospital. The device will now have to undergo secure association with the deployment site, such that it is now loyal to the deployment site and not the manufacturer. This can be achieved by establishing a shared key between the two principals involved namely the hospital and the device. Since both have public key pairs that can be authenticated, i.e the robot is convinced that the hospital has a valid operating license and the hospital is convinced that the device isn't fake or miscalibrated. A simple approach might just be to use Diffie-Hellman key exchange over a physical cable connected to the surgeons console on one end and the robot on the other. Both the robot and the surgeon's console have a screen, so a hash of the key may be displayed and verified manually in the interest of simplicity.

To perform a traceability operation, read request for the robot's calibration certificated will be submitted by the hospital to the access control system. The access control system will check that the security label of the hospital (subject) dominates that of the robot's calibration certificate generated during initial calibration. This is expected to be permitted as the hospital is a few levels above the hospital. If the calibration certificate is successful retrieved and verified, the integrity label of the subject will be increased to that of the parent device (device calibrator). The process is reiterated by the subject to retrieve the calibration certificate of the parent device. At each iteration the integrity level associated with the robot increases. This process carries on until the highest integrity (bottom level of NMI) is reached. Thus calibration traceability of the robot starts at ω_1 at the top level and concludes until it reaches maximal integrity at ω_p.

If the read operation attempts to read from a label with a conflict of interest, or if an attempt was made to read from a lower integrity label than that of the requester, the read will be denied and the

traceability operation will fail, assuming that we have not reached ω_p, the bottom layer NMIs, which is the end point of the traceability chain. In this case, the surgeon knows that the measurement uncertainty of the robots' sensors is not minimised. The hospital might decide to postpone the procedure and get a new calibrator carried out that resolves the conflict of interest, or decide to take the risk and operate. In either case, the risk is identified via a mandatory access control model, and the hospital has the opportunity to address the issue.

4.3 Recalibration

When the expiry date and time has passed, informed by the expiry field in the device's calibration certificate, the device is deemed unfit for measurements or calibration as it may have a higher uncertainty in measurements from before or may be drifting from its norm. Therefore, it must be recalibrated to ensure that its measurements are of the correct accuracy and uncertainty defined by how far it is from the SI units atop the traceability chain.

Recalibration is usually performed by the calibrator who issued the previous certificate for the device. In accordance with our access control model 3, the calibrator can write upwards to the calibration certificate if there is no conflict of interest. This is done under the assumption that calibration units from upper levels are not out-of-calibration.

The recalibration process outputs a new calibration certificate and the previous certificate will be archived, both with the same label as the existing calibration certificate.

4.4 Recalibration arising from certificate revocation

Aside from expiration of a calibration certificate, devices may be recalibrated based on several events. For example, parental calibration units, in the traceability chain with the device as the starting node, may be out of calibration and thus all subsequent units in the chain would require recalibration.

The SI units, from which NMIs calibrate their master calibration units, have recently updated, and so all master units and those below in the chain would need to be calibrated. This is a highly uncommon event, but is still regarded as a factor that affects whether or not devices and units need recalibrating.

5 CONCLUSION

In this work, we have presented a new access control model for surgical robotics. We have highlighted that when we shift to a paradigm in which components of surgical robotics suites are internet-connected, safety-critical problems also become a security problem.

From a problem-space surrounding internet-connected surgical robots to the calibration infrastructure which encapsulates its components, we derive information flow constraints. From this, we developed an access control model, which captures notions of access control from the BIBA, BLP, and Chinese wall models, thus fulfilling confidentiality and integrity requirements across a multi-level hierarchy, whilst compartmentalising hierarchical components so as to avoid conflicts of interest.

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