Practice Update – Improving security and trust for IoT devices during rescue operations

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Abstract

This paper briefly introduces pilot evaluations that have taken place under the umbrella of the First Responder Advanced Technologies for Safe and Efficient Emergency Response (FASTER) initiative, a project co-funded by the European Community and Japan. The FASTER Research Consortium included research organizations, emergency response practitioners, and industry from 11 countries and 23 organizations. This paper concerns a pilot evaluation carried out in Japan in July 2021 to evaluate the technologies developed by European FASTER partners and their interoperability with a distributed network of trust framework created by the Japanese partners. The expected outcome of the evaluation pilot was that the distributed network of trust would enable secure and trustable communications among first responders employing technological tools during rescue operations. This paper presents details of the pilot and the architecture of the technical solutions. Because all the FASTER pilots involve close collaboration with emergency first responders during the design of the pilots and during the pilots themselves, the evaluation of the data obtained from pilots incorporates not only a technological assessment of the distributed network of trust created by the authors of this paper but also initial insights from the practitioners as to the usability of the tools provided by European FASTER partners, as part of the assessment.

Keywords: *Distributed Ledger Technologies, IoT Devices, First Responders*

This paper presents the results of an evaluation pilot held in Japan, which took place on July 26th, 2021, at the Hyogo Prefectural Emergency Management & Training Center and Firefighting School in Miki City, Hyogo Prefecture. A second Japanese pilot was scheduled at the same location in February 2022 with broad participation from most FASTER European partners. However, because of COVID-19 restrictions, the pilot was canceled, and instead, the Japanese team participated in another pilot held by the partners in Madrid, Spain, in April 2022. During these pilots, the Japanese team aimed to evaluate the security and reliability of tools developed during the course of the FASTER initiative.

FASTER contributes to developing a new approach to disaster response, using technology to increase situational awareness and consequently improve first responders' (FR) safety during emergencies. As this paper describes, the Japanese pilot was part of a group of pilots, most of which took place in various European countries. The primary purpose of the Japanese pilot evaluations was to assess a distributed-ledger technology built from the ground up to support real-time quantum-safe[1] communication security of the tools developed by other FASTER team members.

The FASTER project was funded by Horizon 2020 in Europe and The Japan Science and Technology Agency in Japan. The project ran from May 2019 to April 2022 in Europe and from May 2019 to March 2023 in Japan. Despite the global COVID-19 pandemic, which required pilot cancelations and scaling down, the project partners made significant progress in Europe and Japan. However, because of the travel restrictions imposed by governments in response to the pandemic, the project had to evolve. In particular, the Japanese team found it necessary to adapt the original evaluation strategy to evaluate its research efforts by canceling a second Japanese pilot and instead performing additional tests

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[1] Post-quantum cryptography (sometimes referred to as quantum-proof, quantum-safe or quantum-resistant) refers to cryptographic algorithms (usually public-key algorithms) that are thought to be secure against a cryptanalytic attack by a quantum computer.

locally and during a pilot held in Madrid, Spain in April 2022.

Faster Project goals

The following list summarizes the primary goals of the FASTER project (Dimou et al., 2021).

- Data collection to provide a secure IoT platform for distributed, real-time gathering and processing of heterogeneous physiological and critical environmental data from smart textiles, wearables, sensors, and social media;
- Operational capabilities to provide flexible, multi-functional autonomous vehicles, including swarms, for extended inspection capabilities and physical risk mitigation;
- Risk assessment to provide tools for individual health assessment and disaster scene analysis for early warning and risk mitigation;
- Improved ergonomics to provide augmented reality tools for enhanced information streaming, as well as body- and gesture-based interfaces for vehicle navigation and communication;
- Resilient communication at the field level to provide haptic communication capabilities, emergency communication devices, interoperation with K9s, and at the infrastructure level through 5G technologies and Unmanned Aerial/ Ground Vehicles (UxVs);
- Tactical situational awareness to provide innovative visualization services for a portable Common Operational Picture for indoor and outdoor scenario representation;
- Efficient cooperation and interoperability amongst first responders, LEAs (Law Enforcement Agencies), community members and other resource providers, under the umbrella of a secure network of trust, provided by a custom-built distributed-ledger technology that meets the stringent FASTER real time, privacy and security restrictions.

Overall Architecture

The architecture considers a constant interaction between bio-monitoring and situational awareness factors and the FASTER control center. FASTER aims to improve disaster response and monitoring capabilities by providing first responders with a suite of tools to augment their situational awareness and, as a result, enhance their safety and operational capacity. The focus of disaster response is on mitigating the impact of disaster and ensuring the security of first responders during the emergency (Dimou et al., 2021).

FASTER's integration architecture connects various tools and devices through a distributed network of trust called AIngle, built from the ground up to support real-time, quantum-safe security. Each tool and device gathers and shares information with a Common Operational Picture (CoP) panel and a command and control center to coordinate rescue operations. The idea is to take advantage of AIngle's unique and efficient mechanisms to interconnect all technologies developed by FASTER partners and used by the first responders at the edge layer to facilitate secure, encrypted, private, and efficient information traffic. The section below provides more details on the first pilot, which took place at two training fields strewn with collapsed building debris. One field was sponsored by the Japan International Cooperation Agency (JICA); the other by Hyogo Prefecture. In addition, some aspects of pilot training also took place in a large indoor disaster training facility. An overview of the system architecture is provided in Figure 1.

Summary of Previous Pilots

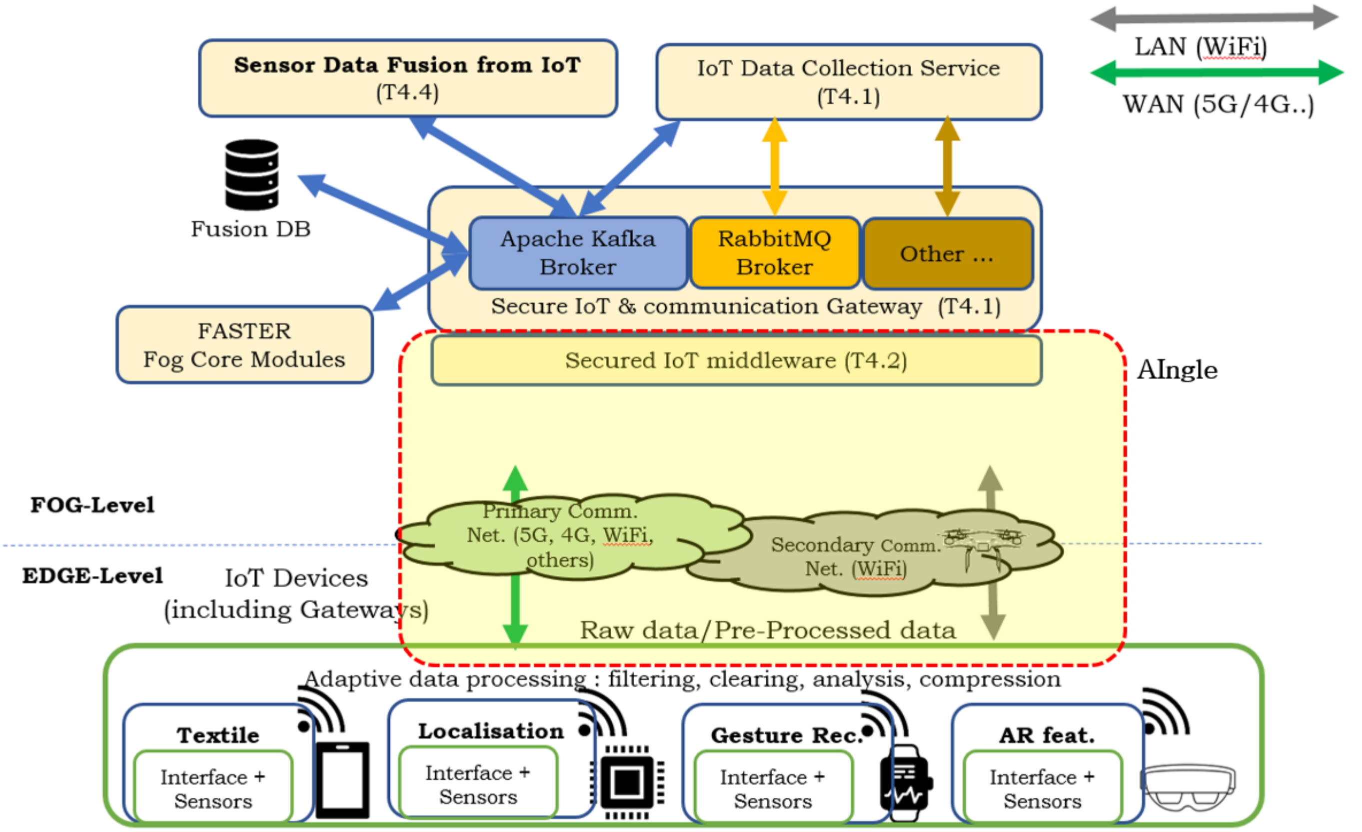
The FASTER project plan called for pilots. It used scenarios to test the impact of the various tools developed by the partners on first responders in rescue situations. Some of the pilots carried out in European partner countries before the Japanese pilot are described below.

Spain Pilot (Madrid)

The first FASTER pilot was held in Madrid in November 2020 (FASTER, 2020, November). The objective was to simulate major earthquake effects and test the efficacy of some of the FASTER tools. However, due to the pandemic, the safety protocols were adapted following the health procedures provided by the community of Madrid (this additional challenge was valuable because it proved the importance of integrated systems in a pandemic environment). The scenario consisted of a 7.3 Richter scale earthquake at 7 am (Madrid local time) and collapsed areas and buildings in hazardous conditions. The pilot involved the fire department of the community of Valencia and the municipal police of Madrid.

In the Madrid pilot, the FASTER technology proved valuable in supporting operational tasks. Through the aerial images transmitted by drones to the control center and 2D or 3D mapping, it was possible to assess the disaster areas and identify the most compromised buildings in real time through the CoP interface. Without the intervention of FASTER tools, the task (assessing a disaster area) would have taken much longer.

Figure 1
FASTER Architecture with AIngle Integration



Communication between people and the control center was smooth despite the limitations of the communication networks. Rescue dogs (K9) were monitored in real time by the CoP.

Italy Pilot (Moncalieri)

The second pilot was held in Moncalieri, a city south of Turin, Italy (FASTER, 2021, May). After several postponements due to the pandemic, it was carried out in January 2021. This pilot recreated a flood (a typical disaster in this area of Italy) that occurred in 2016 after heavy rains flooded several towns near the Apennines, especially Cuneo, Asti, Alessandria, Turin, and Moncalieri. The scenario consisted of a flooding situation after several storms with heavy rainfalls (between 500 and 600 mm). The tools used in this pilot included the Mission Management Tool, or MMT (that the first responders used to send and receive multimedia with geolocated content), a smartwatch that sent information to the control center in real time about the position, status, and activities on the ground.

Furthermore, the situation on the ground was reported through drones to the CoP via 2D and 3D maps. The Control Center communicated with the first responders by sending messages, assigning missions, and sending reports. In contrast, the first responders sent photos and videos to the CoP only via the MMT chatbot (as the smartwatch did not have a camera). In this pilot, all first responders were asked to agree to data sharing with the CoP using voice control and gesture control.

Finland Pilot (Kajaani)

The third pilot simulated a terrorist attack in an indoor environment of a school building in Kajaani, Finland (FASTER, 2021, May). The tools used in this pilot included motion sensors, weather station, and Control Center reports, airflow status (ventilation) and smoke sensors, and dog suits worn by participating K9 units. The pilot considered training reaction procedures in response to a terrorist attack using FASTER technology to improve response and information flow. The first part involved an indoor explosion. The Emergency Response Center then received a terrorist attack alarm and the Kainuu Rescue Department dispatched units to the explosion scene. Smart textiles in rescuers' uniforms allowed continuous monitoring of biometric data, such as heart rate, respiratory rate, body temperature, and blood pressure. The data were displayed on the first responders' devices. When predetermined thresholds were reached, an alert (LED light) was activated, displaying data on a central information hub (CoP). The mobile Augmented Reality (AR) was used as operational support to show the nearest extinguishing and evacuation routes, along with the position and orientation of first responders (using HoloLens). The 3D visualization tool revealed abnormal heat locations, smoke, CO2 values, and route planning reports. In the meantime, the police force set up a perimeter while canine units (K9) performed search and rescue of trapped victims. The pilot recreated an intervention in a classroom with hostages. Canine units with sensors and communication tools were used to maintain continuous information sharing with rescue personnel. It was a successful pilot that included an unpredictable situation (i.e. hostage-taking).

Japan Pilot

Building upon the significant progress achieved during the pilot experiments introduced above, this paper aims to describe the results of the Japanese pilot. The Japanese pilot was held on July 26th, 2021. During the pilot, the Japanese team tested various aspects of AIngle, a distributed ledger technology (DLT) designed and developed in Japan as the communication framework that integrates all the FASTER technological components (See Figure 1). The hypothesis was that AIngle would provide quantum-safe security of interconnections at the edge layer without interfering with the practical use of FASTER tools. To accomplish this, AIngle adopted a well-known approach to post-quantum cryptography by employing hash-based cryptography of all data in and out, in accordance with the Merkle Signature Scheme (Merkle, 1990), thereby guaranteeing that it is impossible to break the cryptography even with a yet-to-be-available quantum computer, as proven by Luis Garcia (Garcia Coronado, 2005). In addition, AIngle needs to meet stringent requirements for data privacy regulations, trustworthiness, and resilience through decentralization, speed, and efficiency. Thus, the pilot experiments described in this paper needed to demonstrate the viability of AIngle and thereby prove the hypothesis while meeting these stringent requirements. The primary focus of the Japanese pilot was the response to an earthquake that caused buildings to collapse. The scenario took place indoors and outdoors. The purpose of the Japanese pilot was to evaluate the viability of the AIngle framework to interconnect various devices and measure data throughput, latency, and reliability. This function is necessary because there are limited—if any at all—DLT frameworks capable of providing real-time interconnection to mission-critical technological solutions employed by first responders in life-or-death situations.

The Japanese pilot incorporated the technologies provided by Horizon 2020, FASTER and other local partners, which are described in Table 1 in the following subsection. Figure 2 illustrates the functional overview

Figure 2
Japanese Pilot Functional Overview

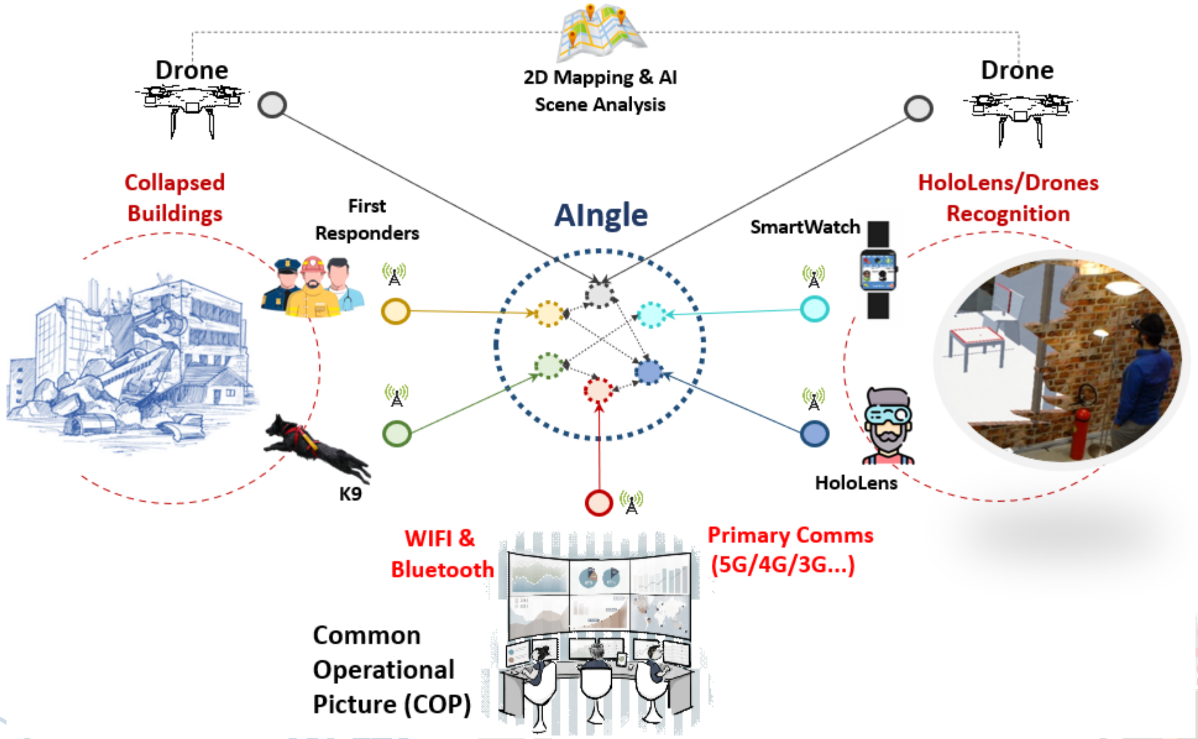


Table 1
Tools tested in first Japanese pilot

Tools / Developer	Hardware / Software	Description
MORSE (MOvement Recognition for firSt rEsponders) Developed by UNIWA (FASTER, 2021b)	Smartwatch Fossil Gen5	MORSE will provide non-visual/non-audible communication capabilities, translate movements or critical readings from paired wearable devices to coded messages, and communicate to cooperating agents on the field through vibrations on wearable devices. The messages will be transmitted using IoT communication protocols (e.g., Bluetooth Low Energy; BLE)
AR Operational Support Developed by CS (CS Group, 2021)	Microsoft Hololens 2	The main aims of the AR system are to visualize the first responder and the team members' position on a map (for an indoor or an outdoor environment) and visualize alerts (related to FR health and immediate hazard) and commands within an intuitive and non-disruptive interface. In addition, the AR system will display on-demand information regarding direct threats, mission information, and its current position on a map.
CoP (Common Operational Picture) Developed by ENG (FASTER, 2021a)	Tablet/Laptop	The FASTER Portable Control Centre allows FR teams to make an efficient and effective decision, use a dynamic interface to show critical situations, and select and organize the proper response. It is a new way to merge and visualize essential information in a CoP, having an overall and continuously up-to-date situation awareness.
2D Mapping AI Scene analysis Extended Vision UxV gesture control Developed by CERTH (Konstantoudakis et al., 2020)	Drones Mavic enterprise2 Microsoft HoloLens2 Smartphone with Android 8 (or higher) Laptop/Tablet	• Extended vision: This tool enables users to view a real-time video from a drone's camera on an augmented reality head-mounted display. • Gesture Control: This tool enables users to control drones using simple, one-handed gestures. • 2D Mapping: This tool will allow first responders to generate an accurate 2D map of the affected area in an automated manner using one or more drones. It is accessed through the CoP, where users can mark the site to be mapped, select the drone(s) that will execute the mission, and designate other mission parameters.
Dog Suite Developed by Tohoku University (Ide et al., 2021)	Dog Suit	Search and rescue dogs perform well in finding victims within 72h in disaster sites. The dogs can tell us the location of victims by continuous barks. However, it is not sufficient for triage, which requires the location and the victims' number, states, and conditions. Tohoku University research proposes a method of recording and visualizing the dog's activities by using robot technologies.
AIngle (Distributed Network of Trust) Developed by KGU	AIngle (Semantic DLT)	A distributed network of trust allows technologies developed by other FASTER team members to communicate securely and independently, without the need for deep integration, while maintaining desired levels of privacy. Thus, a DLT (distributed ledger technology) based on a directed acyclic graph (DAG) has been developed from scratch.

of AIngle with FASTER tools employed during the Japanese pilot.

Japanese Pilot Participants

As mentioned in the introduction, the FASTER project consortium consists of 23 organizations from 10 countries in Europe, and Japan. This multidisciplinary consortium consists of first responders, industrial corporations, and academic institutions. In addition to the FASTER consortium members, local partners in Japan included the Kobe City Fire Department, the Japan Rescue Association, a civil canine trainers' organization, RUSEA (Regional Revitalization & Disaster Prevention Useful Drone Promoters Association), a civil drone operators' group, and the Hyogo Prefectural Emergency Management and Training Center. Also, Tohoku University is providing K9 suits, the first non-FASTER-developed technology to interoperate with the FASTER toolset to demonstrate FASTER's broad applicability.

Venue for the Japanese Pilot

The Japanese pilot took place at the Hyogo Prefectural Emergency Management and Training Center, which is co-located with the Hyogo-based Firefighter's Academy. The center serves as a wide-area disaster prevention base that covers the entire prefecture, provides operational and logistical support during natural disasters, and functions as a hosting facility for disaster emergency personnel. In addition, the center is a hub for training staff, fire brigade members, disaster prevention and response organizations, and leaders. It also carries out disaster prevention training for citizens of the prefecture. The center is part of a much larger Disaster Management Park (see the operations map in Figure 3). The park includes an open athletic stadium, a domed sport, and events stadium, an earthquake simulation facility, a large green park area, and a disaster museum, among other facilities. The total area of the Disaster Management Park is 256 hectares. This prefecture became a nationwide leader in disaster mitigation education following the

Great Hanshin-Awaji Earthquake of 1995 and has many educational and training facilities where first responders and community organizations can organize training for disaster management, prevention, and response. This made the facility an as-close-as-it-gets environment to conduct the experiments for the Japanese pilot.

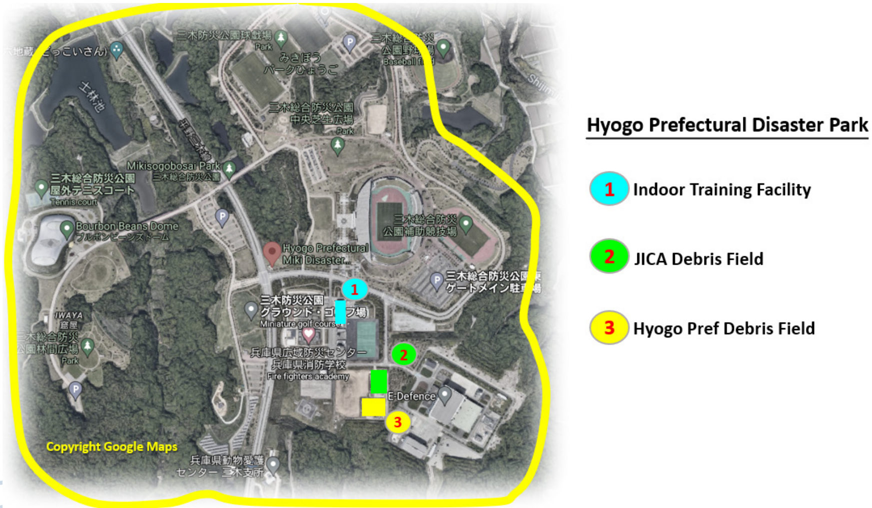
The Japanese pilot took place at two training fields strewn with collapsed building debris on the fields. One field was sponsored by JICA; the other by the Prefecture. In addition, some aspects of pilot training also took place in a large indoor disaster training facility.

The Role of AIngle in the Pilots

This section briefly summarizes the novel AIngle DLT framework. AIngle was constructed from the ground up to support a lightweight, fast and reliable transactional network that enables interconnected IoT devices to support mission-critical distributed smart applications. The etymology of AIngle is a combination of the acronym for “Artificial Intelligence” (AI) and the last four letters of “tangle” (ngle) to form the plural form of the old Scottish word “AIngle” meaning angels or “messengers.” This latter meaning captures the exact purpose of the AIngle framework, which is to act as a messaging platform among participant messaging nodes, i.e., a network of IoT devices. The design and construction of AIngle are intended to meet four important requirements:

- Lightweight. Support for IoT nodes with low computational power and low memory capacity.
- Fast. Support for distributed applications that can process real-time transactions and support encrypted gossip of streamed data.
- Reliable. Support for ad hoc IoT networks, which may or may not have a connection to the Internet.
- Powerful but light consensus. Support for a feeless, energy-efficient consensus algorithm.

Figure 3
Pilot venue at a certain Disaster Management Park



AIngle is inspired by IOTA.org which is also based on the DAG[2] graph-based structure. Although AIngle improves many of the techniques introduced by IOTA.org, its most notable contribution is that AIngle incorporates a distributed knowledge graph database capable of supporting the development of knowledge-oriented or intelligent applications. This distributed knowledge graph database supports highly interconnected data by providing a concept-level schema (or ontology) that fully implements the Entity-Relationship (ER) model. To accomplish this, AIngle enables the distribution of knowledge graph shards through their inclusion in AIngle nodes, wherever they might be needed to support the creation of intelligent applications.

The underlying AIngle knowledge graph database adapts an early version of TypeDB, developed by Vaticle.com (formerly known as Grakn.ai), a type system that implements knowledge representation and reasoning principles. Through TypeDB, AIngle enables the construction of distributed smart applications by providing an expressive distributed graph modeling language to perform deductive reasoning over large numbers of knowledge graph shards distributed among AIngle nodes. With this distributed knowledge graph structure, AIngle effectively became the first DLT that supports distributed knowledge for artificial intelligence and distributed cognitive computing systems, called “Smart Distributed Applications.” While upcoming papers will contrast Smart Distributed Applications with much-hyped Smart Contracts by highlighting their common traits and significant differences, this paper aims to focus on its role in the FASTER project and to evaluate its viability for mission-critical applications such as disaster first response.

Security and Trust Concerns

The need to introduce a robust system such as AIngle to manage edge-layer communication for interoperating rescue technologies might not be obvious at first glance. However, the following examples of cyber-attacks

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[2] DAG stands for Directed Acyclic. A DAG is a graph that is directed and without cycles connecting the other edges.

and infrastructure failures make a strong case for introducing the AIngle framework as a distributed network of trust for real emergency rescue operations.

- Recently, cyber-attacks seem to be more prominent in headline news. The Colonial Pipeline Ransomware Cyber Attack that stopped the flow of gas throughout the Eastern United States and the Qbot trojan attack suffered by Japanese Company Fujifilm (Fujifilm, 2021) are some examples. In Fujifilm's case, although its network was partially shut down and disconnected from external correspondence to protect the business, their operations were down for almost four days, including global operations such as healthcare, imaging, workplace services, and materials. These types of cyber-attacks are very damaging. They can be even more dangerous if they occur during a disaster and affect ongoing rescue operations. For instance, if hackers were to take over a rescue drone, or a rover, or even take over the computerized equipment or control the command center, the effect on rescue operations would be catastrophic. In the best scenario, it could result in the loss of private data; in the worst scenario, it could result in the loss of human life. AIngle's primary role is therefore to prevent cyber-attacks through a distributed network (DLT) that encrypts all information shared. This distributed network of trust uses encryption algorithms to prevent malicious intrusions. In addition, a distributed ledger ensures decentralization of the database, thus generating a network of trust among participant elements of the FASTER ecosystem.
- Smooth and resilient communication among first responders and other stakeholders is vital during catastrophic events. Any interruption in transmission during an emergency can hinder rescue operations. For instance, during the devastating floods in the Uttarakhand National Park in India in 2013 (Kishorbhai & Vasantbhai, 2017), a large-scale black-out caused an interruption in communication, resulting in thousands of casualties due to the inability of rescue teams to maintain smooth communication. This event highlighted the need for the development of a system that could withstand sudden connectivity outages. AIngle provides resilient communication mechanisms among devices and tools even in the event of internet outages because it can create ad hoc local networks. Once internet connectivity is restored, AIngle is also capable of updating the main AIngle network (a.k.a. SemDAG).

How Can AIngle Address these Security and Reliability Concerns?

AIngle has been evaluated so far through benchmarking experiments and compared to two other well-known distributed ledger technologies, namely, Ethereum and Iota.org. The results of these benchmark experiments can be seen in Table 2.

As Table 2 shows, AIngle's performance in terms of experimental Transactions Per Second (TPS) is significantly better than that of Ethereum and Iota.org, whereas IOTA has better theoretical TPS scalability because it handles a much larger number of nodes than AIngle. As AIngle's nodes increase in number, it is anticipated to perform at the same level or better than IOTA. However, AIngle's performance in natural disaster scenarios needs further evaluation. For this reason, the Japanese pilots aim to perform a series of experiments, which will evaluate:

1) Speed. These experiments aim to answer whether response times meet the requirements necessary to respond in rescue operations.
2) Reliability. These experiments focus on assessing how reliable the AIngle framework can be during rescue operations. The investigation involves stress tests and Internet connectivity tests by disconnecting from the Internet to test whether the local connections can support the communication requirements through AIngle ad hoc connections.

Exit interviews and questionnaires will be employed to gather important information from first responders to assess the usability of the AIngle framework and other FASTER technologies used during the pilot. This paper presents all the results from these experiments.

As mentioned in the introduction, the key hypothesis is that AIngle will provide quantum-safe security of interconnections at the edge layer, without interfering

Table 2
Tools tested in first Japanese pilot

DLT	Operation	TPS[a]	Theoretical TPS Scalability[b]	Execution Time (In Seconds)[c]
Ethereum	Blocks	13.1	16	
Iota	Tangle	108.0	18,000	
AIngle	Semantic DAG[d]	1,240.0	10,800	

[a] Transactions Per Second.

[b] Ethereum Scalability taken from WP (https://ethereum.org/en/whitepaper/#scalability).

[c] Time elapsed between sending and receiving data

[d] A Semantic Directed Acyclic Graph (Similar to the Tangle, but with a distributed graph database).

with practical use. Thus, after successful completion of the first pilot evaluation targets, the second pilot will focus on evaluating whether AIngle is also able to meet a series of stringent requirements for security, data privacy regulations, trustworthiness, and resilience through decentralized smart applications. As the results of the experiments described below prove, AIngle is capable of meeting the above series of requirements. The evaluations below show that by the end of the Japanese pilot, the AIngle met speed and reliability tests.

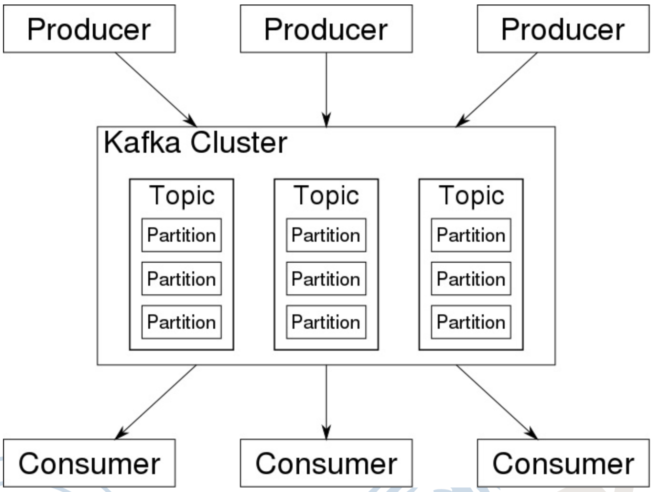
Important Pilot Considerations

Before introducing the evaluation results of the first Japanese pilot for FASTER, it is important to point out a few key points to highlight the significance of the results.

First, as Figure 1 illustrates, AIngle sits at the edge layer of the FASTER architecture. What this means is that all technological components employed by first responders within the FASTER umbrella could be connected to other layers through AIngle. In reality and for practical reasons, the FASTER architecture currently uses Apache Kafka (Kreps et al., 2011) as a messaging platform to provide a one-stop interconnection at the edge layer. Although this is a fairly common approach for interconnecting various systems with minimal integration costs and effort, it is also a fairly insecure approach as it depends on a centralized architecture. As depicted in Figure 4, the Kafka architecture consists of a cluster of segmented services called Topics. A topic can be loosely defined as a channel to which so-called producers can write and so-called consumers can read data. Partitions can be loosely interpreted as sub-services that provide granular functionality. In the context of FASTER, a technological component that, for example, sends sensor data can be considered a producer. Consumers can be any technological component that reads or consumes those services. To illustrate, a producer could be a drone that is pushing its GPS location while generating a 2D map of the affected area. The consumer could be the CoP that is reading the GPS position to display it in real time at the CoP. The same data could be also consumed by the service that stitches together the images being produced by the drone. This service then produces the final 2D map and publishes it to Kafka, and the CoP, in turn, consumes the 2D map to superimpose it on the CoP interface.

Figure 4

Apache Kafka overview



In the first pilot, for practical reasons, it was necessary to create a Kafka broker that acts as a go-between between AIngle and Kafka to measure the speed and reliability of AIngle. In the second pilot, the broker will only play a secondary role, as FASTER components will communicate directly with AIngle. This will enable us to test other aspects of the AIngle framework such as data anonymization and end-to-end encryption, which is currently not provided by Kafka.

Another important consideration, which is necessary to understand the scope of the AIngle evaluation during the first pilot, is that AIngle basically has two kinds of nodes: Light nodes and perma-nodes. A light node, as the name implies, is a node that stores very small amounts of hashed data in the form of Merkle trees for the Semantic DAG. This information is what is relevant to the light node. A perma-node is a node that stores larger amounts of data relevant to a network or subnetwork of nodes that use it as a storage bin. In the pilot evaluation, it was necessary to use a single perma-node because of the temporary limitations introduced by the Kafka broker approach. Thus all of the AIngle network and its Semantic DAG are stored there.

Because the Kafka broker is directly connected to a so-called AIngle perma-node—a full node capable of producing, consuming, and, more importantly, storing the data—we can observe a very interesting phenomenon. Figure 5 illustrates the topological shape of the Semantic DAG resembling a worm. This, of course, is due to the fact that there is only one perma-node. In order to achieve the full potential of AIngle, all IoT devices and other FASTER components need to incorporate an AIngle light node to be able to interact with more than one perma-node depending on the resources available to other components in their immediate vicinity. In this case, we expect the topology of AIngle to transition to the topology depicted in Figure 6.

Figure 5
The shape of Semantic DAG created during the first Japanese Pilot

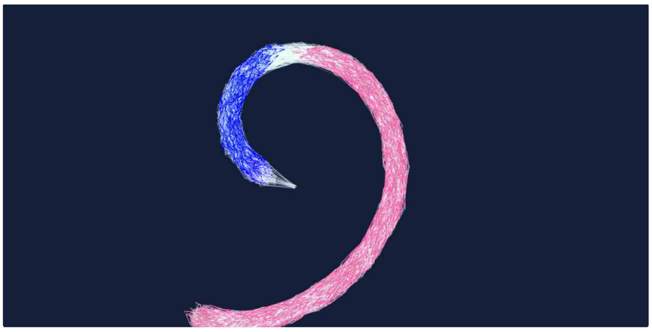


Figure 6
The expected shape of Semantic DAG during the second Japanese Pilot

With these considerations in mind, let's now describe the positive results obtained from the pilot evaluation in the following section.

Evaluation Results

On the day of the pilot evaluation, AIngle was able to provide data writing and reading service to a total of 105 topics; 49 of which were topics generated by the FASTER technical components connected through Kafka to AIngle, while the remaining 56 were internal support topics produced by the AIngle to Kafka broker. There were also 317 Kafka partitions generated and the same number of Kafka partition replicas, indicating that there was a one-to-one relation with the partition. This can be interpreted as an indicator of the stability of write-read roundtrip transactions. If the numbers were different, this would represent compensation for data loss, none of which occurred during the day of the evaluation.

It is important to note that the pilot tried to simulate a very realistic disaster scenario. The site of the pilot sits in an area with inconsistent internet connectivity. The internet was available only through 4G connections and it was unreliable. The average temperature on the day of the pilot evaluation was around 34°C with about 70% relative humidity, which translates to a heat index of about 47°C. Some of the devices, such as PCs, smartphones, drones, HoloLens 2 AR glasses, etc., did not operate optimally and sometimes would stop working altogether, even after applying dry, quick cooling sprays to reduce the heat generated by these devices. Despite these harsh conditions, AIngle performed better than expected.

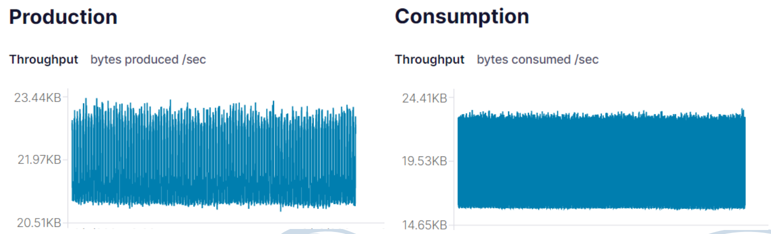
Reliability

Even under the very harsh conditions on the day of the evaluation, the results for data throughput were significantly positive as demonstrated in Figure 7. Production of data written to AIngle through Kafka occurred at an average of 21.31 Bytes/second, while the total data throughput was between 21 and 23.44 Kilobytes/second (see Figure 7a). Consumption of data occurred at an average of 22.94 Bytes/second for a total data throughput between 15 and 24 Kilobytes/second (see Figure 7b). These are averages per connection for the 105 topics generated and interacting with the AIngle framework, which means that the framework was very reliable and that despite the Internet connection was unreliable, the data was partitioned such that no data loss occurred.

Speed and Availability

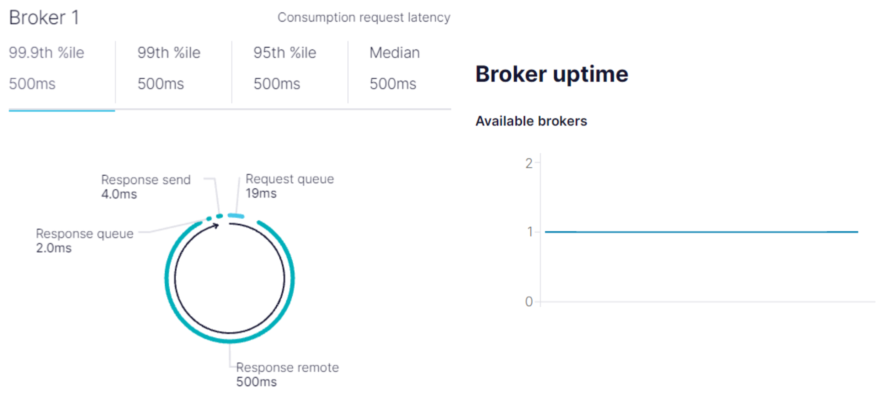
Figure 8, although a Kafka table, demonstrates that the AIngle framework also performed admirably with regard to read/write speeds. Figure 8a unequivocally shows that all the read/write transactions occurred within 25 milliseconds, which is the reason why 99.9% were within the 500-millisecond category in the figure. This exceeds expectations and validates AIngle as a first-of-a-kind DLT for IoT interconnections. On the other hand, Figure 8b demonstrates the Kafka broker, which writes to and reads

Figure 7
AIngle data throughput during the first Japan Pilot



a) Average throughput of 21.31 Bytes/second b) Average throughput 22.94 Bytes/second

Figure 8
AIngle data latency and reliability during the first Japan Pilot



a) Average latency is about 25 milliseconds for processing requests and responses by AIngle

b) Even under very realistic conditions with very unreliable internet, a single broker was up 99.9% of the time

from all the devices into AIngle, was available 100% of the time. Furthermore, Figure 9 depicts the total data throughput that occurred through the Kafka broker on the day of the pilot. In total, the amount of data was approximately 9.5 Gigabytes.

In conclusion, the data depicted in Figures 7 through 9 demonstrate the viability of the AIngle framework for real-time as well as mission-critical applications such as those required of FASTER tools by disaster first responders.

First Responder Questionnaire Evaluation

The organizing team distributed the Japanese-translated version of the uniformed questionnaire developed by FASTER to evaluate usability by first responders. In the case of the first Japanese pilot, first responders included five firefighters, two K9 units and 2 handlers, one drone operator, and one venue manager. Only five firefighters and two supervisors, who observed the pilot, responded to the questionnaire after the pilot. All questionnaires were answered in Japanese. An English translation was used for the analysis presented in this section.

It is worth mentioning that the questionnaire was focused on subjective evaluation of the FASTER tools provided by the European partners and did not include any question about AIngle, as AIngle is transparent to the first responders. Responses focused on subjective end-user experiences in using the FASTER tools provided by European partners, which included both hardware and software tools. For end-users, these two are treated as one. Therefore, the responses did not include AIngle functionality because of its transparency to the user experience.

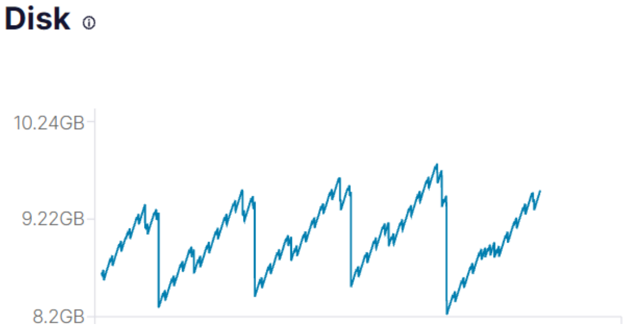
Figure 10 shows the number of respondents according to each tool. All the respondents evaluated MORSE and AR tools for operational support. Four firefighters evaluated UxV gesture control, three firefighters evaluated the 2D mapping, and one firefighter evaluated the CoP.

Questionnaire Evaluation

Analysis of the questionnaire indicates the following important points per tool:

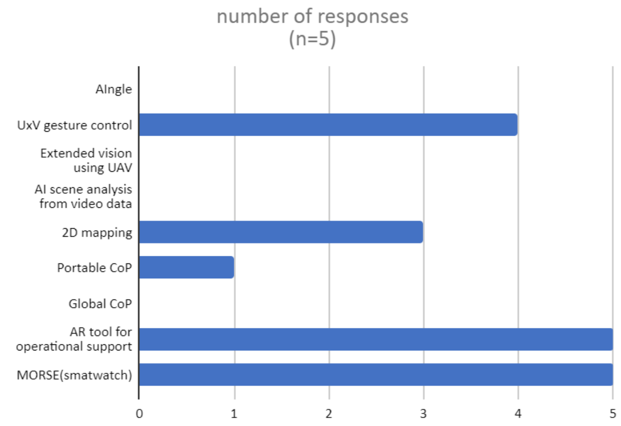
MORSE**:** The firefighters highly praised MORSE's accuracy and transmission, compared with the radio. On the other hand, they mentioned the dysfunction of signals, as MORSE mistakenly recognized even small body movements as gestures. Also, some firefighters mentioned the difficulty of complex operations.

Figure 9
AIngle data latency and reliability during the first Japan Pilot



Total Data Consumption data throughput was 9.5GB with no data loss, during the day of the first Japanese pilot evaluation even with a very unreliable internet connection due to the remoteness of the pilot site.

Figure 10
Number of responses to the first responders' questionnaire by tool



AR Operational Support: The firefighters highly praised the accuracy and the usability of the visualized information. On the other hand, all the firefighters who participated in the pilot mentioned the vulnerability of the AR glasses to heat. Also, they mentioned the difficulty of complex operations as they expressed trepidation when using AR glasses in the debris field for fear of damaging the equipment while searching for survivors.

Common Operational Picture (CoP)**:** The firefighter who participated in the CoP operation expressed satisfaction with the centralized situational awareness provided by the tool. On the other hand, one firefighter who did not operate the CoP was skeptical of a centralized CoP. It should be noted that other firefighters who did not operate the CoP had conflicting opinions regarding the use of the CoP at the rescue site.

2D Mapping: One firefighter expressed satisfaction with 2D mapping of the disaster site, and mentioned that he had seen some other institutions using similar systems effectively to gain a better understanding of the disaster area.

UxV gesture control**:** One firefighter, who used this tool, suggested that hand gesture drone control was extremely satisfactory. This firefighter went as far as to say that of all the tools evaluated on the day of the pilot, it was perhaps the only one tool that could be used as is, with minor improvements in real rescue operations. On the other hand, one firefighter, who did not use the tool, expressed skepticism about using gestures to control a drone at the disaster area.

Overall**:** Here are three main points summarizing the overall comments from firefighters about the FASTER tools evaluated during the pilot.

Firstly, more effort should be invested in simplified usability of the tools. Although the organizing team had two training sessions for firefighters beforehand and provided the training materials as handouts and posters on site, the firefighters did not feel fully prepared to use the tools during the day of the pilot.

Secondly, it was suggested that the hardware should be more stable and durable to operate under harsh, rugged conditions of real disaster area conditions, such as heat, dust, smoke, rain and other natural phenomena. In particular, during the day of the pilot the temperatures reached 34°C with 70% relative humidity. Under these conditions, which equate to a 47°C heat index, hardware often malfunctioned. Although some measures to reduce the impact of heat, such as applying dry quick-cooling sprays directly onto the devices, helped, the constant heat made it impractical to use the devices for extended periods of time.

Thirdly, the electronic communication environment should be improved. Because real disaster situations are less likely to have good network connectivity, the researcher should provide a feasible solution for the provision of electronic network connectivity quickly on-site. Although this did not affect the usability of AIngle as demonstrated in this paper, it did have a negative impact on the use of some of the tools, which would lose connection to the network sporadically.

Finally, it is important to note that all respondents praised the potential of FASTER tools for future use in real disaster response. Considering the question *do you think FASTER tools bring added value to your work?,* one respondent out of five responded *They add much value*. Three out of five responded *They add value enough to make them attractive*, although one of three added a note *I hope it will add value in the future*. Finally, one responded *They add some value* (See Figure 11).

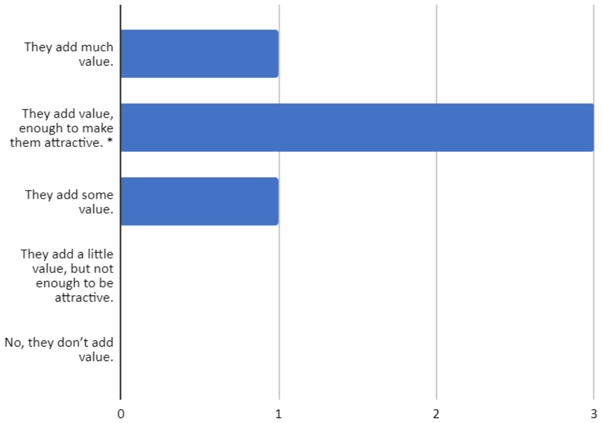
Having that said, some respondents expressed important criticisms. For instance, one respondent suggested:

> *Because all the tools are not usable as is, my response to this questionnaire would be negative at present, but if the main issues can be cleared, these tools would be attractive in the future... Regarding the idea to manage the information from each tool on a single PC (via the CoP), I think that we do not need to have it in usual Japanese disaster situations.*

Aside from the above response, some other respondents also used the word *future* in their responses, which connotes that the FASTER tools are still in work-in-

Figure 11

Responses to question Do you think FASTER tools bring added value to your work?



progress and have room for improvement before their actual use.

Conclusion

Overall, we can conclude that the Japanese pilot successfully demonstrated the viability of the AIngle framework in terms of speed and reliability, which are very important requirements for any real-time, mission-critical interconnection framework to support first responders in life-or-death situations. One future goal for AIngle is its ability to create a distributed smart application capable of providing real-time anonymization of private data being produced and consumed through AIngle (for example, masking the faces of people included in images or video produced and consumed through the AIngle framework). Another remaining future goal is the robustness of the encryption provided by the Merkle hash trees used in AIngle. To accomplish these two goals, a follow-up evaluation experiments will interconnect more devices than the Japanese pilot described in this paper. But rather than using a broker for Kafka, all devices will incorporate a lightweight AIngle plug-in that will enable those devices to become active nodes of the AIngle Semantic DAG. Moreover, instead of just producing or consuming data directly from AIngle, the devices will also support the smart applications that will provide the anonymization services needed to ensure privacy according to the strict privacy requirements of GDPR[3].

During the follow-up evaluation experiments, AIngle will not rely on a Kafka broker to communicate with the FASTER toolbox. Thus, it will be possible to evaluate the security of the AIngle framework through standard penetration testing techniques. The authors are confident that as the framework is theoretically quantum-safe, the evaluation will demonstrate that it meets the high standards for security required in mission-critical applications. As for other FASTER tools—provided by European partners—evaluated during the pilot, it is important to pay attention to the impressions provided by first responders, as described in the *First responder questionnaire evaluation* section. Certainly, the valuable feedback provided by Japanese first responders will help improve the usability and user experience of these tools.

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[3] European General Data Protection Regulation.

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