Xronos: Predictable Coordination for Safety-Critical Distributed Embedded Systems

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Abstract—Asynchronous frameworks for distributed embedded systems, like ROS and MQTT, are increasingly used in safety-critical applications such as autonomous driving, where the cost of unintended behavior is high. The coordination mechanism between the components in these frameworks, however, gives rise to nondeterminism, where factors such as communication timing can lead to arbitrary ordering in the handling of messages. In this paper, we demonstrate the significance of this problem in an open-source full-stack autonomous driving software, Autoware.Auto 1.0, which relies on ROS 2. We give an alternative: Xronos, an open-source framework for distributed embedded systems that has a novel coordination strategy with predictable properties under clearly stated assumptions. If these assumptions are violated, Xronos provides for application-specific fault handlers to be invoked. We port Autoware.Auto to Xronos and show that it avoids the identified problems with manageable cost in end-to-end latency. Furthermore, we compare the maximum throughput of Xronos to ROS 2 and MQTT using microbenchmarks under different settings, including on three different hardware configurations, and find that it can match or exceed those frameworks in terms of throughput.

I. INTRODUCTION

Frameworks such as the Robot Operating System (ROS) [1] and MQTT [2], [3] are widely used in safety-critical, concurrent, and often distributed applications such as autonomous driving and industrial automation [4], [5], [6]. These frameworks are convenient, modular, and their underlying asynchronous coordination mechanism, called publish-subscribe (pub-sub), is easy to use and not prone to deadlocks. This paper empirically shows that pub-sub is ill-suited for such applications and offers an alternative: an open-source middleware called Xronos built on top of an open-source coordination language, LINGUA FRANCA (LF) [7]. LF, based on the reactor model [8], is a polyglot coordination language that borrows the best semantic features of established models of computation, such as actors [9], logical execution time (LET) [10], synchronous reactive languages [11], and discrete event systems [12] such as DEVs [13] and SystemC [14]. LF further supports asynchronous injection of external events, and once a

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logical time has been assigned to such events, their handling is
deterministic. We show that this determinism does not incur a
significant performance cost on three test platforms, a PC, an
NVIDIA Jetson AGX Xavier, and a heterogeneous two-node
distributed embedded system.

For distributed embedded systems specifically, how to deal
with faults and degradations is application-dependent. If com-
munication latency increases, for example, some applications
will require timely reactions even with incorrect or inconsis-
tent data, whereas for other applications the correctness of
responses is more important than their timeliness. For example,
an emergency braking system may prefer to apply the brakes
with incomplete sensor data, whereas a car may prefer to delay
entering an intersection when sensor data is incomplete or
inconsistent.

Brewer’s CAP theorem [16] shows that no system can have both consistency (here, conformance with the application
specifications) and availability (here, timely reactions) when
the network is partitioned. This paper proposes two distributed
coordination mechanisms, both implemented in Xronos. One
emphasizes availability over consistency, and the other empha-
sizes consistency over availability when the network fails or
degrades. The first mechanism, our decentralized coordinator,
is an extension of PTIDES [17], a real-time technique also
implemented in Google Spanner [18], a globally distributed
database. This coordinator is also influenced by Lamport [19],
and Chandy and Misra [20], [21].

The second mechanism, our centralized coordinator, is an
extension of the High-Level Architecture (HLA) [22], a
distributed discrete-event simulation standard. Our extensions
adapt HLA’s techniques to make them usable not just for
simulation, but also for distributed real-time deployment where
unpredictable asynchronous events are injected via sensors.

The decentralized coordinator ensures software components
continue to react even if the communication latencies increase,
whereas the centralized coordinator ensures the software com-
ponents behave as specified even if their inputs are delayed.
Hence, the decentralized coordinator emphasizes availability
over consistency, whereas the centralized coordinator empha-
sizes consistency over availability when the network degrades.

The rest of this paper is organized as follows: We give
background on state-of-the-art frameworks for distributed
embedded systems, Autoware.Auto, and LF in Sec. II. We
demonstrate three specific issues in Autoware.Auto with em-
pirical evidence in Sec. III. We explain the design of Xronos
and detail our extensions to LF in Sec. IV and offer imple-
mentation details in Sec. V. Finally, we evaluate Xronos
on microbenchmarks and Autoware.Auto in Sec. VI, give
an overview of related work in Sec. VII, and conclude in
Sec. VIII.

II. BACKGROUND

A. Pub-Sub Frameworks for Distributed Embedded Systems

ROS\(^1\) is a collection of tools and libraries that facilitate the
development of robotics applications. Developers can package
software modules as independent entities called nodes. Each node will live in its own separate process on a host
operating system. Nodes can co-exist on a single machine
or be distributed across multiple and communicate over the
network. Irrespective of physical location, nodes communicate
using a pub-sub model, in which publishers advertise topics
and subscribers bind a specific callback function to a topic. ROS 2, which we use in this paper, utilizes a DDS-compliant
communication framework [23] to implement the pub-sub
mechanism. We identify this underlying pub-sub as a potential
source of concurrency errors that affect the application logic
and are hard to detect and remedy (see Sec. III). MQTT [24]
is a TCP/IP-based pub-sub protocol with similar properties
that is widely used in Internet of Things applications.

B. Autoware

Autoware is an open-source software for autonomous vehi-
cles based on ROS. Autoware.Auto\(^2\) is the current generation
of Autoware, and is a successor to the previous version called
Autoware.AI. Autoware.Auto is based on ROS 2 and features
a modular design, consisting of a variety of nodes that are
capable of perception, localization, planning, and control.

Fig. 1\(^3\) shows the collection of nodes that are present in
Autoware.Auto release 1.0 (black edges portray pub-sub
“topics,” blue edges delineate actions, and red edges illustrate
services). These nodes together form a pipeline that is capable
of “autonomous valet parking,” where the vehicle can go and
park autonomously anywhere in a parking lot.

Autoware.Auto’s modular design enables execution on a va-
riety of platforms in a distributed manner. For communication
among distributed nodes, Autoware.Auto mainly uses pub-sub
messages and asynchronous callbacks. The distributed design
of Autoware.Auto allows concurrent execution of various tasks
on dedicated hardware; however, this also makes it challenging
to achieve reproducible system behavior.

C. Lingua Franca

LINGUA FRANCA (LF) is an open-source polyglot coordina-
tion language that emphasizes deterministic interaction
between concurrent reactive components called reactors [7],
[25], [8]. We have chosen LF as the basis for our work because
of its deterministic semantics. Events in LF are tagged and can
be sent from a port of one reactor to the port of another. Every
event occurs at a logical tag \(g\) drawn from a totally-ordered
set \(\mathbb{G}\) and every reactor processes events in tag order. Each
tag is a pair of numbers, a timestamp \(t \in \mathbb{T}\) and a microstep
\(m \in \mathbb{N}\) (to realize superdense time [26]). A timestamp \(t \in \mathbb{T}\)
represents a measure of time.

\(^1\)https://www.ros.org/
\(^2\)https://www.autoware.org/autoware-auto/
\(^3\)Produced based on output from the rqt-graph ROS package.
external events can be injected into the system with the use of scheduled dynamically through a runtime API. Asynchronous periodic events, while actions provide sporadic events that are variables are local to a reactor instance, and can be read or replaced with a measurement of physical time. State to specify a of relayed events. Alternatively, the ∼ after (Ln. 20). The main reactor (Ln. 2) showing syntax (keywords are in bold, metavariables are italicized), target languages (currently C, C++, Python, TypeScript, or polyglot in the sense that reactions are written in one of several languages while application code has access to both the logical clock (tags) and the physical clock on the local platform. By default, logical time “chases” physical time in a program execution, so that events with a logical time t occur close to (but never before) physical time T = t. Reactions may have deadlines that guide an earliest deadline first (EDF) scheduler. Application code can provide a deadline handler, fault-handling code to be invoked instead of a regular reaction when a deadline is violated.

Execution of an LF program must ensure that each reactor reacts to events (input messages, timer events, and actions) in tag order. If two events have the same tag, they are logically simultaneous, and no reaction at that tag can observe one event as present and the other as absent. Moreover, along any communication channel between reactors and for any timer or action, there can be at most one event with any given tag g.

Our main contribution in this paper is to extend these properties across a distributed system, thereby preserving determinism. We extend LF to allow top-level reactors to become independent processes (federates), deployable to remote machines. This extension includes handling of a multiplicity of physical clocks and permitting federates to independently advance their local tags. Our extensions enable all existing valid LF programs that use the C target (where reactions are written in C/C++) or the Python target to be transparently converted to federated programs. It also supports specification of fault handling code that is invoked when communication latencies increase enough to make it impossible to enforce the consistency requirements specified in the program while keeping the program responsive.

III. MOTIVATIONAL CASE STUDY: AUTOWARE.AUTO

To demonstrate the degree to which pub-sub-based communication methods can undermine confidence in safety-critical applications, we consider Autoware.Auto, a full-stack autonomous driving framework that uses ROS.

A. Node-to-Node Inconsistency

Consider the subsystem of Autoware.Auto depicted in Fig. 3a. The State Report topic includes state information about the vehicle, including the current gear. Consecutive messages published by the LGSVL Interface (the interface to
the vehicle, a simulator in our case) on this topic are always delivered in the order they were sent. For example, if the gear is reported as “drive” in one message and as “reverse” in the next, then the Behavior Planner will see that the vehicle has been in the “drive” gear and subsequently switched to “reverse.” This order is crucial for the Behavior Planner to correctly keep track of the current state of the vehicle and to make accurate safety-critical decisions in general.

Notice that the LGSVL Interface node also publishes messages on the Vehicle Kinematic State topic, which includes information such as the current velocity (positive for forward movement and negative for reverse) and the wheel angle of the vehicle, among other details. However, messages published on these distinct topics may be delivered in arbitrary order; the pub-sub semantics provides no built-in means to order messages across the two independent message flows.

The Behavior Planner simply stores the gear information upon receiving the State Report. Upon receiving the Vehicle Kinematic State, it then uses the stored gear data to calculate and publish a new trajectory for the vehicle. The output of the Behavior Planner depends on the order in which these messages arrive. Imagine the following test scenario, where the LGSVL Interface publishes messages in the following order: (1) “drive” on State Report; (2) Vehicle Kinematic State with a positive velocity; (3) “reverse” on State Report; and (4) Vehicle Kinematic State with a negative velocity.

The Behavior Planner can observe the produced message sequence in any permutation that preserves the ordering of messages within the same topic, which we confirmed empirically. Fig. 3b shows the incidence of observed message sequence permutations as a percentage of the total number of complete message sequences published. In our experiments, we varied the rate at which the LGSVL Interface node produces sequences of (1) → (2) → (3) → (4). The period after which the sequence repeats is shown on the y-axis. We chose periods that correspond to the frequency at which sensors typically produce data in the real world. We ran each test $3 \times 10^9$ times on an Ubuntu PC with an AMD Ryzen 5800X CPU and 32GB of DDR4 memory running ROS 2 Foxy.5

One would normally expect the message sequence observed at the Behavior Planner to be the same as it was published by the LGSVL Interface. It would only be reasonable to expect the interface and the planner to agree on the state trajectory of the vehicle. However, disagreement about the order of events can lead to inconsistent views on the state of the system, and can make the outcome of tests misleading.

Consider the sequence (1) → (2) → (4) → (3), which can be observed under minimal stress on the ROS 2 infrastructure. In this permutation of the published message sequence, the vehicle is in the “drive” gear (1) and reports a positive velocity (2). However, before the state of gear can be updated to “reverse” (3), the Behavior Planner will receive a negative velocity state (4). This state has to be treated by the application developer either as a genuine fault condition, or be dismissed as an inconsequential inconsistency introduced by the ROS framework. In the former case, tests will transiently fail. In the latter case, tests will not fail, but this comes at the cost of not being able to detect a dangerous system state that might occur while the system is operating.

Even if the dangerous state is treated as a legitimate error, without any stress on ROS, a test that checks for this condition will pass 99.8% of the time. This can lull the application designer into a false sense of confidence in the safety of the application. Of course, infrequent errors due to message sequence permutations can be made more frequent by applying stress on the ROS 2 framework. We also ran our test scenario under stress, depicted in Fig. 3c with periods smaller than 1 millisecond. This test puts pressure on the underlying message delivery infrastructure by flooding it with messages.5 Under stress, the ROS framework buckles, and delivers messages across topics in a multitude of seemingly unpredictable permutations. While the expected observation order is still in the majority, the error rate is two orders of magnitude higher than in Fig. 3b. We also observe messages being dropped due to limited buffering capacity in the DDS framework, causing odd message patterns such as (3) → (1) → (2) → (3).

One solution to the node-to-node inconsistency problem is to consolidate topics. But this severely impairs the modularity of the application and the reusability of components. In the case of Autoware.Auto, the State Report gets published in a superclass of the LGSVL Interface, which publishes the Vehicle Kinematic State. The two topics have different uses, and their data are sourced from different subsystems entirely (the CAN bus and GPS/GNSS, respectively). Another solution would be

4The DDS runtime used here is Eclipse Cyclone. Other DDS implementations could give more repeatable behavior. However, our goal is not just repeatable behavior, but a deterministic semantics.

5This method is somewhat inspired by chaos engineering techniques [27].
to explicitly tag each message (e.g., using sequence numbers) within the LGSVL Interface and do manual alignment. This approach, however, carries significant overhead and is error-prone. We propose to solve the problem in the communication layer, where it can be done more robustly and efficiently while keeping the application simple and modular.

### B. Multi-node Inconsistency

The asynchrony of pub-sub communication poses further challenges. Consider another subsystem of Autoware.Auto, depicted in Fig. 4a. In it, the MPC Controller produces a Vehicle Command (not depicted) on the basis of several inputs, including a Trajectory and a Vehicle Kinematic State. Upon receiving any input, the MPC Controller will try to recompute the Vehicle Command. The problem of multi-node inconsistency concerns the alignment of the observed inputs. To compute an accurate Vehicle Command, all inputs must relate to the same frame of reference [28], but due to the asynchronous communication between nodes, they typically do not.

In our experimental setup, the Behavior Planner takes an average of 75 milliseconds to compute a new Trajectory upon receiving a Vehicle Kinematic State. The Vehicle Kinematic State is produced with a frequency of 30 Hz, resulting, on average, in 2.48 messages being received at the MPC Controller for each Trajectory. As a consequence, the latest Vehicle Kinematic State is always newer than the latest Trajectory. Therefore, the MPC Controller attempts to transform the last received Vehicle Kinematic State to the frame of reference of the last received Trajectory, a costly operation that could be eliminated if proper alignment was ensured by an underlying framework.

One could argue that transforming inputs to match the desired frame of reference is a satisfactory solution [28]. While this may be true for variables such as velocity, which only marginally change over the span of a few seconds, it is not the case for variables that encode modes and thus are subject to discrete changes. The presence of these kinds of variables raises potential for “mode confusion” [29] in the control system, a situation where the system executes invalid logic with respect to its current mode. We found that such scenario can also occur in Autoware.Auto.

Consider the subsystem shown in Fig. 4b. Whenever the Behavior Planner decides that it is time to brake and start backing up into a parking space, it notifies the MPC Controller with a Trajectory that tells it to stop the vehicle. Simultaneously, the Behavior Planner sends the LGSVL Interface a “reverse gear” State Command. It would certainly be dangerous if the vehicle interface were to attempt to change gear before reaching a full stop. To prevent a serious error like this, the Autoware.Auto designers use a complicated state machine in the implementation of the LGSVL Interface that ensures that all Vehicle Command messages are handled before performing the gear change requested in the State Command. In our opinion, this needlessly clutters the application logic with error-prone code. It would be much better if the underlying framework would automatically provide proper alignment.

### IV. DESIGN OF XRONOS

The issues raised in Sec. III can be automatically avoided if the semantics of LF are honored in a multi-process or distributed setting. However, there are several non-trivial challenges involved in making a transition from the currently implemented multi-threaded LF runtimes to multi-process/distributed ones. In this section, we discuss the design of our main innovation, the Xronos federated runtime for LF. We establish a transparent workflow that takes ordinary LF programs and turns them into federated ones, in which reactors are mapped to processes that can be deployed to remote machines, jointly constituting a federation.

#### A. Startup and Shutdown

**Startup:** In LF, there exists a start tag $g_s$ such that all logical timelines for all reactors of a program start at $g_s$. In non-federated LF implementations, $g_s$ is set to a reading of a shared physical clock. This approach does not extend well to a distributed system without access to a shared clock, where clock synchronization is imperfect and communication delays have to be accounted for. Instead, we implement a distributed consensus in which, during a startup stage, a central coordinator called the RunTime Infrastructure (RTI, the name adopted from HLA [22]) is started. Each federate first synchronizes its physical clock with the RTI (see Sec. V-C for details). Next, each federate reports a reading from its physical clock and shares it with the RTI. The RTI collects a list $\Phi_g$ of proposed start times and chooses $\max(\Phi_g) + d$ as the start time for all federates, where $d$ is a value chosen automatically based on measured communication delay and federation size.

**Shutdown:** A deterministic shutdown is especially important in safety-critical applications where external factors might require a timely, but deterministic shutdown of the system (think of an advanced autopilot system being turned off). Since a federation is already running, the shutdown problem can be formulated as a logical consensus. If a federate decides to stop the execution, it ceases to advance its tag and notifies the RTI. The RTI will then ask other federates for an appropriate final tag (which in turn causes the other federates to pause processing events). After receiving all tags, the RTI picks the
maximum tag and sends it to all federates, which will then process all remaining events up to and including this tag.

B. Advancing Logical Time

To honor the semantics of reactors, each federate must see events in tag order and not start processing events with a tag larger than events that could later be produced by upstream federates. In ordinary LF programs, all reactors must finish processing events with tag \( g \) before any reactor may start processing an event with tag \( g' > g \). Such a barrier synchronization would be very costly in a federated implementation. We instead have realized two more loosely coupled coordination methods: our centralized and decentralized coordinators.

1) Centralized Coordination: For each federate \( f \), the RTI keeps track of the following information:

1. **LTC\(_f\): Logical Tag Complete.** A record of the most recently received tag from federate \( f \) notifying the RTI that it has completed all computation and sent all outgoing messages with that tag or less. The value of LTC\(_f\) is initially \(-\infty\), a special tag smaller than all other tags.

2. **NET\(_f\): Next Event Tag.** This is the most recently received tag from a federate \( f \) reporting the earliest event in its event queue. If a federate’s event queue is empty, it will send \( \infty \), a special maximal tag. If the RTI has not received a NET message from the federate, the value is \(-\infty\).

3. **TAG\(_f\): Tag Advance Grant.** This is the tag most recently sent to federate \( f \) to permit \( f \) to advance its current tag to TAG\(_f\). The value of TAG\(_f\) is initially \(-\infty\).

Each federate \( f \) conveys the first two quantities to the RTI in a **Next Message Request** (NMR\(_f\)) message at the start of execution and at the completion of each tag. The payload of the message is \((\text{LTC}_f, \text{NET}_f)\), where \( \text{LTC}_f < \text{NET}_f \). The very first NMR message will carry \( \text{LTC}_f = -\infty \) because no event has been processed. The TAG\(_f\) is sent by the RTI to each federate \( f \) to permit it to advance its tag. At all times, the RTI and the federates may have only partial information, and messages conveying these quantities may be in flight and not have been recorded.

When the RTI receives an NMR message from federate \( f \), it may respond with a **Tag Advance Grant** (TAG\(_f\)) message, possibly not immediately. It may also send TAG messages to downstream federates. Let \( D(f) \) be the set of immediate downstream federates (those that receive messages directly from \( f \)), and let \( U(f) \) be the set of immediate upstream federates (those that send messages directly to \( f \)). Suppose the RTI receives an NMR message from \( f \) with payload \((\text{LTC}_f, \text{NET}_f)\). First, it updates its data structure to register these two new values. Then it does two things:

1. For all \( \forall d \in D(f) \), let

\[
g_d = \min_{u \in U(d)} (\text{LTC}_u + a_{ud}),
\]

where \( a_{ud} \) is the minimum “after” annotation on connections from federate \( u \) to \( d \). If \( g_d > \text{TAG}_d \), then the RTI sets \( \text{TAG}_d = g_d \) and sends a TAG message to federate \( d \) with payload \( g_d \). This tells the downstream federate \( d \) that it may advance its current tag to \( g_d \) and process any events or inputs that it has received with that tag or any earlier tag. The RTI is sure to have forwarded all messages to \( d \) with tags equal to or less than \( g_d \) because all federates upstream of \( d \), including \( f \), have reported completion of execution at logical tag \( g_d \) or larger.

2. The RTI determines whether it can grant a tag advance to \( f \), in which case it will send it a TAG message. If \( \text{TAG}_f \geq \text{NET}_f \), then there is nothing to do because the RTI has already granted such a tag advance to \( f \). Otherwise, if \( \text{TAG}_f < \text{NET}_f \), then the RTI needs to compute the **Earliest Incoming Message Tag** (EIMT\(_f\)) for federate \( f \). This is defined as follows:

\[
\text{EIMT}_f = \min_{u \in U(f)} (\min(\text{EIMT}_u, \text{NET}_u) + a_{uf}).
\]

If \( U(f) = \emptyset \), then we define EIMT\(_f\) = \( \infty \). Note that because EIMT appears on both sides, this is a system of equations. As long as the logical delays satisfy \( a_{uf} \geq 0 \), it is easy to prove that there is a maximal solution (which may have \( \infty \) for some federates), even in the presence of cycles, and we have implemented a simple iterative procedure for finding that maximal solution. If EIMT\(_f\) \( \geq \text{NET}_f \), then let \( \text{TAG}_f = \text{NET}_f \) and send a TAG message to \( f \) with payload \( \text{NET}_f \). Otherwise, the RTI does not reply. The federate will have to wait until it gets a TAG as a consequence of (1).

When a federate \( f \) sends to the RTI an NMR with payload \((\text{LTC}_f, \text{NET}_f)\), it is stating that:

- It will never again send a message with tag \( g \leq \text{LTC}_f \), and it would be an error for it to receive any incoming message with such a tag (such a message is said to be tardy, and a main task of the centralized controller is to guarantee that no tardy messages occur).

- Until the federate receives a TAG\(_f\) > LTC\(_f\), it will not send an outgoing message with tag \( g < \text{NET}_f \). Once it receives a TAG\(_f\) > LTC\(_f\), then it can advance its current tag to TAG\(_f\) and send a message with tag \( g \geq \text{TAG}_f \) (it can be TAG\(_f\) + a\(_{fd}\), where \( a_{fd} \) is the “after” delay on the connection to \( d \)).

If federate \( f \) has no physical actions, then NET\(_f\) is simply the tag of the earliest event on its event queue, or \( \infty \) if the event queue is empty. However, if \( f \) has physical actions, it can make no such promise until \( T_f > \text{NET}_f \), where \( T_f \) is the current physical time at federate \( f \), since an event might appear with timestamp \( T_f \). In this case, in order to permit downstream federates to advance time, federate \( f \) needs to repeatedly send NMR messages as its physical time advances. Here there is an inherent tradeoff between network bandwidth and time granularity. These messages need to be frequent, but not too frequent.

Fig. 5 shows the sequence of messages under centralized coordination that ensures alignment for the sub-architecture of Autoware in Fig. 4a. The MPC Controller will not process the received vehicle kinematic state message \( \forall g \) until it receives a \( \text{TAG}(g) \) message from the RTI. The RTI in turn ensures that the MPC Controller receives the \( \text{TAG}(g) \)
message only after it has received the trajectory message $\mathcal{T}_f$, allowing the MPC Controller to process $V_f$ and $\mathcal{T}_f$ logically simultaneously at tag $g$.

2) Decentralized Coordination: We give here a realization of PTIDES [17], [30] with substantial extensions.

For each federate $f_i$, we will derive $S_i \in \mathbb{T}$, a safe-to-process (STP) offset. Given $S_i$, a federate will not be able to advance to any tag $g = (t, m)$ until its physical time $T_i$ satisfies

$$T_i \geq t + S_i.$$  \hfill (1)

where $T_i$ is a measurement of physical time on the platform executing $f_i$. If $f_i$ includes any physical action, then $S_i \geq 0$. Otherwise, it can be positive, negative, or zero. The purpose of $S_i$ is to ensure that by the time the physical clock satisfies (1), all events that may have originated on some other federate with tags less than $g$ have previously arrived at $f_i$. This ensures that events can be processed in tag order.

Next, we discuss the assumptions needed to calculate $S_i$.

a) Launch Deadline: Assume that a reaction $r$ invoked at tag $g$ in $f_i$ is able to send a message to another federate $f_j$. It does this simply by writing to an output port of $f_i$. We assume that $r$ is invoked before physical time $T_i$ exceeds $t + D_{ij}$, where $D_{ij}$ is the launch deadline. As mentioned in Sec. II-C, violation of such a deadline can be detected using existing semantics of LF. It is worth noting that our runtime interprets a lower deadline as having a higher priority. Also note that it must be true that $D_{ij} \geq S_i$ because no reaction in LF can be invoked at tag $g = (t, m)$ before physical time $T_i \geq t + S_i$.

b) Launch Lag: We define the launch lag as

$$L_{ij} = D_{ij} - S_i.$$  \hfill (2)

The launch lag $L_{ij}$ represents the physical time that elapses between the start of execution of the step at tag $g$ and the invocation of reaction $r$. It must include the execution time of any reaction(s) that are invoked before $r$ at this tag plus any scheduling overhead, and hence it must be nonnegative. The launch lag may be zero if this overhead is negligible.

c) Communication latency bound: We also need to assume a bound $N_{ij}$ on communication (either inter-process or network) latency. This is defined as the maximum physical time (by the clock at federate $f_i$) that passes between the invocation of the reaction $r$ that sends the message and the receipt of the message at federate $f_j$. This time includes not just the propagation time through the communication channel (sockets in our case), but also the execution time of $r$ and any overhead in the network stack.

d) Clock synchronization error bound: Finally, we also need to assume a bound $E_{ij}$ on the clock synchronization error between federates $f_i$ and $f_j$. That is, the physical clocks of $f_i$ and $f_j$ do not drift apart by more than $E_{ij}$.

Calculating the Safe To Process Offset. Assume that $f_i \in F$ sends an event to federate $f_j \in F$ with tag $g = (t, m)$. With the aforementioned bounds, $f_j$ will receive the message before $f_i$’s physical clock reaches $t + D_{ij} + N_{ij}$ and before its own physical clock reaches $t + D_{ij} + N_{ij} + E_{ij}$.

The connection from $f_i$ to $f_j$ may alter the tag (using the after keyword), incrementing it by $a_{ij} \geq 0$. Since the event is launched by a reaction invoked at $t$, the event with timestamp $t' = t + a_{ij}$ will be received by $f_j$ before its physical clock exceeds $t + D_{ij} + N_{ij} + E_{ij}$. Equivalently, $f_j$ receives an event with tag $g' = (t', m')$ before its physical clock exceeds $T_j = t' + D_{ij} + N_{ij} + E_{ij} - a_{ij}$. \hfill (3)

If $a_{ij}$ is large enough, it can even be true that $T_j < t'$, in which case, at physical time $T_j$, the receiving federate will have received all messages with timestamps $t \leq T_j$.

We can now generalize to any number of federates. First, let $a_{ij}$ be the minimum delay (specified using after) over all connections from $f_i$ to $f_j$. Let

$$M_{ji} = \max(0, D_{ij} + N_{ij} + E_{ij} - a_{ij}).$$  \hfill (4)

Here, if $i = j$, $E_{ij} = 0$, and $N_{ij}$ is a bound on the latency with which the federate sends messages to itself (this could be zero as well). If there is no connection from $f_i$ to $f_j$, then $a_{ij} = \infty$. $M_{ji}$ represents a relative safe-to-process offset for $f_j$ with respect to $f_i$.

We can now write down an expression for the safe-to-process offset $S_j$,

$$S_j = \max_{i \in F}(M_{ji}).$$  \hfill (5)

However, from (2), we have

$$D_{ij} = S_i + L_{ij},$$

so the safe to process offsets appear on both sides of this equation. Therefore, we have a system of equations that must be solved. Rewriting (4) to make this explicit, we get,

$$M_{ji} = \max(0, S_i + L_{ij} + N_{ij} + E_{ij} - a_{ij}).$$

To simplify this, let

$$X_{ij} = L_{ij} + N_{ij} + E_{ij} - a_{ij}$$

and write

$$M_{ji} = \max(0, S_i + X_{ij}).$$

We can now write

$$S_j = \max_{i \in F}(M_{ji}) = \max(0, \max_{i \in F}(S_i + X_{ji})).$$  \hfill (6)

We now have $n$ equations in $n$ unknowns.

Max-Plus Formulation. Equation (6) can be written compactly and solved easily using a Max-Plus formulation [31]. Let $X$ be a matrix where the $i,j$-th element (row $i$, column
Let $S$ be a column vector where the $i$-th element is $S_i$. Then note that in Max-Plus algebra,
$$
J = XS
$$
is a column vector where the $j$-th element is $\max_{i \in F}(S_i + X_{ji})$. Let $O$ be a column vector where the $j$-th element is $0$. Then note that (6) can be rewritten in Max-Plus algebra as
$$
S = O \oplus J = O \oplus XS.
$$
From [31] (Theorem 3.17), if every cycle of the matrix $X$ has weight less than zero, the unique solution of this equation is
$$
S = X^* O,
$$
where the Kleene star is (Theorem 3.20)
$$
X^* = I \oplus X \oplus X^2 \oplus \cdots
$$
and that this reduces to
$$
X^* = I \oplus X \oplus \cdots \oplus X^{n-1},
$$
where $n$ is the number of federates. If there are cycles with zero weight, but all weights are nonpositive, then there is a solution and a unique minimal solution.

The requirement that the cycle weights be nonpositive is present in the original PTIDES.

For a federate $j$, Xronos will optimistically replace $X_{ij}$ with $T_j - t$ for a given tag $g = (t, m)$ if the status of events for all connections from $i$ are known at $g$.

C. Fault Handling

Without exception, the correctness of a system implementation is predicated on certain assumptions. For example, operating conditions, such as temperature or humidity, need to be within a certain range. Typically, violation of the assumptions leads to a fault condition. In LF, with its sophisticated model of time, special attention is given to faults related to broken assumptions regarding time. Specifically, one can associate a deadline with a particular reaction, along with a fault handler. The fault handler gets invoked instead of the reaction in case it is not ready to execute by the specified deadline. When the centralized coordinator is used in Xronos, the deadline fault handler can be used by the user to detect and react if the underlying communication channel is partitioned or assumptions about execution times are violated.

When the decentralized coordinator is used in Xronos, there is another type of time-related fault that can occur. Specifically, a message from one federate to another could be tardy, meaning it arrives after the receiving federate has already advanced to a tag greater than the incoming message. This can only happen, of course, if the asserted STP offset was not large enough to account for upstream delays, meaning that an STP violation occurred. To allow the user to react to such a violation, we added a new syntax to LF for the specification of the STP, along with a handler to be invoked when it is violated, emulating the style of the existing deadline construct.

V. IMPLEMENTATION

Xronos is a runtime implementation for Lingua Franca, an open-source coordination language built on the basis of the reactor model. At the time of writing, LF supports C, C++, Python, TypeScript, and Rust as targets. Any LF program using the C/C++ or Python targets can run on Xronos. The functionality for this gets enabled simply by changing the main keyword to federated. Support for Xronos in the TypeScript target is under development. Fig. 6 illustrates the integration between Xronos and LF as well as the steps involved in constructing a federated program.

A. Additions to the Language

The example LF code in Fig. 7 highlights our additions to the LF grammar. We added several target properties, which are meant to configure a program and its execution environment in various ways. For instance, we added an option to select a coordination type, an option to create Docker images, and several configuration options pertaining to the clock synchronization mechanism provided by Xronos. We further add the serializer keyword to the language to allow the programmer to specify a serialization mechanism for data exchanged between federates. The at keyword was introduced for mapping federates to specific hosts. Finally, we added a reserved reactor parameter called stp_offset that can be used to specify an STP offset, as well as syntax for defining STP violation handlers.

B. Federated Runtime

The federated runtime is written in C and uses sockets for communication. The entire runtime is approximately 8100 lines of code. Xronos works in conjunction with our modified C and Python code generators that automatically treat reactor instances in the top-level reactor as federates and map them to independent processes. The code generators also transform connections between federates such that the communication gets routed through a socket connection using special sender and receiver reactions. Depending on the coordination type, communication will either happen directly between federates (decentralized) or through the RTI (centralized). For logical connections, the receiver reaction is triggered by a logical action that is scheduled by the federated runtime upon message receipt. The tag of the event that triggers the receiver reaction is determined by the tag that is sent along with the incoming message. For physical connections, the receiver reaction is triggered by a physical action. The tag associated with the triggering event is thus based on physical time as measured by the receiver. Hence, messages sent along physical connections

![Fig. 6: Xronos and LF: compilation process.](image)
target C {
  coordination: decentralized, // Or "centralized"
  clock-sync: on, // Turn on runtime clock sync
clock-sync-options: {
    period: 5 msec, // Clock sync period
    trials: 10, // Num. of msgs used in clock sync
    attenuation: 10 // Stabilize clock sync
    ... other parameters
  },
docker: true, // Produce a docker image
timeout: 10 secs, // Distributed timeout
tracing: true // Distributed tracing
}
reactor Source {
  output out:int
  reaction(startup) -> out (=
    SET(out, 1); // Send data over socket
  )
}
reactor Destination (stp_offset: time(7 usec)) {
  input in:int;
  reaction(in) (=
    info_print("%d", out); // Print the received data
  )
  STP (=
    // Handle input that violates tag order
  )
}
federated reactor Example at user1@host1 {
  c = new Source() at user2@host2
d = new Destination() at user3@host3
  c.out -> d.in serializer "native" // Or ros2, proto
}

Fig. 7: An example federated program.

do not carry a tag. This type of connection is the closest equivalent to the connections used in ROS and MQTT.

C. Physical Clock Synchronization

Xronos can work with clock synchronization based on NTP (default in most systems) or the higher precision PTP [32], [33]. We also provide a built-in clock synchronization implementation realized using the technique of Geng et al. [34]. This ensures that federated execution initializes as expected even if the host system lacks proper configuration or means of clock synchronization. Xronos also optionally corrects for clock drift during execution.

D. Reusing MQTT and ROS Libraries and Nodes

LF is already designed to seamlessly incorporate (legacy) target code and reuse existing libraries. To ease the transition to Xronos, we have prepared a number of examples that demonstrate how to integrate existing ROS or MQTT applications into Xronos-based federations. We also added cmake build support to the C target of our modified lfc compiler and introduced target properties for customizing the cmake build configurations to allow for more convenient integration with the colcon build system used by ROS 2.

E. Serialization

To send data from one federate to another, the data must be converted to a byte stream (it must be serialized) and converted back to the appropriate data type at the receiver (it must be deserialized). Xronos currently supports three serialization schemes: native, proto, and ros2. In C, the native technique directly copies the memory map of the

data to the byte-array that is sent over the socket. This method of serialization can be dangerous and only works if the data type is Plain Old Data (POD) [35] and if the memory format and endianness are the same for the sender and receiver. Nonetheless, this method is fast, and thus useful for some embedded applications. In Python, the pickle module is used to perform native serialization. The proto serializer uses Protobufs, where libproto or its variants are automatically used to serialize and deserialize data. As with any proto-based serialization, the data format is expected to be stored in a .proto file which is then compiled and made accessible in the program. Lastly, ros2 uses the serialization framework of rclcpp. Only ROS 2 messages, services, and actions are supported as a data format. This functionality is particularly important for porting legacy code from ROS 2 to Xronos, enabling developers to reuse ROS 2 message and service data types (e.g., PointCloud2).

F. Deployment

We added support for a deployment strategy based on Docker [36] by generating Docker images for each federate, if requested, and a Docker compose file that simplifies the task of starting the federation, even in a hybrid heterogeneous system.

VI. EVALUATION

We first discuss our port of Autoware.Auto and measure the error rates under Xronos for the scenarios that were discussed in Sec. III. We also compare the end-to-end latency of Autoware.Auto in ROS 2 against our port to Xronos. Subsequently, we supplement our performance evaluations with a set of microbenchmarks to measure the impact of different subsystems in Xronos, such as the built-in Protobuf serialization mechanism, on maximum throughput.

A. Autoware.Auto

We ported Autoware.Auto release 1.0 to Xronos, including its autonomous valet parking functionality. We use our port to measure error rates under both realistic and unrealistic periods for the sub-architecture of Fig. 3a. First, we verified that

---

7https://docs.python.org/3/library/pickle.html
8https://developers.google.com/protocol-buffers/
9https://github.com/ros2/rclcpp
centralized coordination yields zero errors over 300k test runs. With decentralized coordination, errors become possible, but we found no errors for periods down to one millisecond (with an STP offset of 5 ms). With periods below one millisecond, errors begin to appear, but, unlike the ROS 2 implementation, they are detectable (as STP violations). Moreover, by increasing the STP offset, the error rate can be reduced. We found, however, that with periods of 100 µs and below, the STP offset had to become quite large (several seconds) for the error rate to drop to zero, as shown in Fig. 8. Such periods are unrealistic for this application. For applications with such periods, more specialized hardware and networking may be required to eliminate errors.

We would expect that such an improvement in reliability would incur a cost, and, indeed, under centralized coordination, the cost is significant for this application. Under decentralized coordination, we find that the cost in end-to-end latency is considerably lower.

To evaluate the cost for this application, we measured the end-to-end latency from sensor measurements (at the interface to the LGSVL simulator) through the production of a new trajectory in the lane planner to the construction of a vehicle command to feed back to the LGSVL simulator. First, we note that our evaluation still involves two unported ROS 2 components, the LGSVL simulator itself and the built-in tf2 library, which performs frame transformations. These components are not part of Autoware.Auto, but they are needed to construct a full simulation. Also, note that the end-to-end latency includes not just communication overhead, but also the computations needed for planning. The goal of the experiment is to compare the overall behavior of Xronos compared to ROS 2 for a realistic application.

In Fig. 9, we have plotted a cumulative distribution function (CDF) as a function of latency.

Under centralized coordination, the latency is much higher, suggesting that centralized coordination would not be a good choice for this application. This is not surprising because, with centralized coordination, multiple control messages need to be exchanged for transmission of each useful data message, and all communication between federates goes through the RTI. The microbenchmarks, which we consider next, also show that the communication overhead of centralized coordination is quite high, suggesting that this strategy would only be acceptable if occasional errors cannot be mitigated.

However, under decentralized coordination, the cost in end-to-end latency becomes considerably more manageable, but not negligible. Nonetheless, we conjecture that for safety-critical distributed embedded applications, the overall reduction in the error rate could justify this cost.

To further clarify the source of the additional overhead in Xronos, we measured the end-to-end latency of our port using all physical connections, where, as previously explained in Sec. II-C, the inherent determinism of LF is sacrificed. As depicted in Fig. 9, the resulting latency roughly matches that of the decentralized coordination. This suggests that the added logic in decentralized coordination that ensures determinism is not the main source of the added latency. We leave further optimizations of the Xronos runtime as future work.

B. Microbenchmarks

To supplement our results, we consider three distinct communication patterns, shown in Fig. 10, inspired by patterns introduced by Lee and Lohstroh [37], to evaluate the throughput of Xronos as a middleware. We develop microbenchmarks for these patterns in Xronos, ROS 2, and MQTT and measure the maximum throughput, comparing our decentralized coordinator against the state-of-the-art to establish a baseline for comparison. We also measure the throughput of Xronos under the centralized coordinator and measure the impact of various features in Xronos on throughput. We run our tests on three platforms, a desktop PC (the same system used to obtain the results in Sec. III), an NVIDIA Jetson AGX, and a hybrid scenario where nodes/federates are distributed across the PC and the AGX.

Comparison with baseline: Fig. 11 shows the maximum throughput (in Mbps) under Xronos using decentralized coordination compared against ROS 2 and MQTT. For this series of comparisons, the data size is 4 bytes and the STP offset in Xronos is statically calculated for each benchmark (all in the order of a few milliseconds). These measurements are obtained by forcing each benchmark to flood the network and measuring the total physical time at the receiver for the total messages received after running the test for 10 seconds (logical in the case of Xronos and physical for ROS 2 and MQTT, giving an advantage to the latter). Each test is run at least 30 times. For these microbenchmarks, we observe that Xronos can provide
TABLE I: Maximum throughput (in Mbps) of physical connections under different coordinations.

| Coordination | S1-PC | S2-PC | S3-PC |
|--------------|-------|-------|-------|
| Decentralized | 8.16 Mbps | 2.35 Mbps | 2.66 Mbps |
| Centralized   | 5.81 Mbps | 1.34 Mbps | 1.54 Mbps |

TABLE II: Maximum throughput for each supported serialization method, measured over 30 runs, for S1 (in Mbps).

| Serialization | Avg | Max  | Min  | Std  |
|---------------|-----|------|------|------|
| Native        | 4.04 Mbps | 4.27 Mbps | 3.88 Mbps | 0.11 Mbps |
| ROS 2         | 1.19 Mbps | 1.22 Mbps | 1.17 Mbps | 0.2 Mbps |
| Proto         | 2.50 Mbps | 2.57 Mbps | 2.41 Mbps | 0.05 Mbps |

TABLE III: Maximum throughput with and without clock synchronization for S1 (in Mbps).

| Coordination | Clock Sync Mode | Max. Throughput |
|--------------|-----------------|-----------------|
| Decentralized | Disabled | 10.14 Mbps |
|               | Startup-only    | 8.16 Mbps |
|               | Enabled         | 7.54 Mbps |
| Centralized   | Disabled | 6.48 Mbps |
|               | Startup-only    | 5.81 Mbps |
|               | Enabled         | 5.26 Mbps |

a higher throughput than ROS 2. Xronos also has a higher throughput than MQTT for S1 and S2, but falls short in S3 due to the strict alignment requirement at the Sink.

Centralized vs. Decentralized: While the centralized coordinator imposes a strict global ordering of events, it does so with additional overhead both in terms of extra control messages and inserting the RTI as a bottleneck for message communication. Our decentralized coordination mechanism instead relies on assumptions about the latencies in the system to ensure correctness. Fig. 12 shows the comparison between our coordinators. The results show that our decentralized coordinator performs better overall, particularly for the challenging pattern of S3.

Physical vs. Logical: Not all parts of the system need a strict tag ordering in order to function well. To allow flexibility, we have also added support for physical connections across federates, as explained in Sec. V-B. This communication mechanism is the closest match to ROS 2 or MQTT that Xronos offers. Results are shown in Table I. We find that physical connections for these microbenchmarks have up to 7x higher throughput compared to logical connections.

Overhead of Serialization: A benefit of Xronos is that the serialization method used is flexible. Table II shows the overhead per message for the three currently supported serialization methods. We find that while our native method allows for the highest throughput, Protobuf serialization is also substantially more performant than ROS 2 serialization.

Overhead of Clock Synchronization: We measured the throughput of Xronos with and without the built-in clock synchronization mechanism. The results, shown in Table III, indicate that the impact on throughput of our built-in clock synchronization is relatively low. We also found that the clock synchronization error in our method is generally below 10 microseconds.

Federation Scalability: Finally, we tested the scalability of Xronos when number of nodes and message size is increased. The trends that we observed are depicted in Fig. 13. We find that throughput roughly scales down linearly with the number of nodes and message size.

VII. Related Work

Distributed coordination is a decades-old research topic. Classic solutions include Chandy and Misra [20], Jeffer-son [38], and HLA [22]. PTIDES [30] offers a decentralized approach, later independently developed by Google Span-ner [18]. Loosely time-triggered architectures (LTTA) [39], [40] provides a programming model built upon the strictly synchronous TTA model [41], generalizing to distributed environments. System-Level LET (SL LET) [42] extends Logical Execution Time (LET) [10] to distributed settings by relaxing the synchronization requirements. The reactor model can also be viewed as a generalization of the LET principle, enabling combinations of logical execution time with the zero execution time semantics of synchronous languages while preserving the ability to precisely control the timing of interactions with the physical environment.

Runtime systems are further developed based on these coordination schemes. The PRISE project implements a distributed real-time simulation system based on HLA [43]. Ptolemy-HLA framework [44] provides distributed simulation for cyber-physical systems. TipFrame [45] and LETT [46] are examples of LET-based frameworks. DEAR [47] is a discrete-event framework for AUTOSAR [48], an emerging industry standard for automotive software based on reactors. Our work has overlaps with all of these, as any system solution would, but contributes novel extensions to distributed coordination mechanisms that preserve determinacy under clearly-stated assumptions, provide for detection of violations of the assumptions, and provide for handling of the resulting fault conditions.

VIII. Conclusion and Future Work

We have shown that nondeterminism in widely-used pub-sub communication frameworks is potentially dangerous and
can lower the confidence in safety-critical distributed embedded applications.

We have extended the LINGUA FRANCA coordination language to support federations while preserving its deterministic semantics, and we have shown that the cost in performance is manageable. We give two distributed coordination mechanisms: a centralized one that emphasizes preserving the program semantics even in the presence of network failures, and a decentralized one that emphasizes being able to continue to make forward progress in the presence of network failures. We provide a mechanism for specifying fault handlers that are triggered by violations of safe-to-process bounds.

Xronos is under active development. There are two main areas for future work: (1) Federate recovery, where if a federate fails, the federation would have the capacity to continue to operate, and (2) Mutation, where the structure of the federation would be allowed to change at runtime.

REFERENCES

[1] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, A. Y. Ng et al., “Ros: An open-source robot operating system,” in ICRA workshop on open source software, vol. 3. Kobe, Japan, 2009, p. 5.

[2] A. Stanford-Clark and U. Hankeler, “Mq telemetry transport (mqtt),” Online. http://mqtt.org. Accessed September, vol. 22, p. 2013, 1999.

[3] R. A. Light, “Mosquito: server and client implementation of the mqtt protocol,” Journal of Open Source Software, vol. 2, no. 13, p. 265, 2017.

[4] S. Kato, S. Tokunaga, Y. Maruyama, S. Maeda, M. Hirabayashi, Y. Kitukawa, A. Monrow, T. Ando, Y. Fujii, and T. Azumi, “Autoware on board: Enabling autonomous vehicles with embedded systems,” in 2018 ACM/IEEE 9th International Conference on Cyber-Physical Systems (IC CPS). IEEE, 2018, pp. 287–296.

[5] I. Malavolta, G. Lewis, B. Schmerl, P. Lago, and E. A. Lee, “How do you architect your robots?” state of the practice and guidelines for ros-based systems,” in 2020 IEEE/ACM 42nd International Conference on Software Engineering: Software Engineering in Practice (ICSE-SEIP). IEEE, 2020, pp. 31–40.

[6] B. Mishra and A. Kertz, “The use of MQTT in M2M and IoT systems: A survey,” IEEE Access, vol. 8, p. 201 071–201 086, 2020.

[7] M. Lohstroh, C. Menard, S. Bateni, and E. A. Lee, “Toward a lingua franca for deterministic concurrent systems,” ACM Transactions on Embedded Computing Systems (TECS), Special Issue on FDL’19, vol. 20, no. 4, p. Article 36, May 2021.

[8] M. Lohstroh, “Reactors: A deterministic model of concurrent computation for reactive systems,” Ph.D. dissertation, EECS Department, University of California, Berkeley, Dec 2020. [Online]. Available: http://www2.eecs.berkeley.edu/Pubs/TechRpts/2020/ECCS-2020-235.html

[9] G. A. Agha, “Abstracting interaction patterns: A programming paradigm for open distributed systems,” in Formal Methods for Open Object-based Distributed Systems, IFIP Transactions, E. N. Stefani and J.-B., Eds. Chapman and Hall, 1997, Conference Proceedings.

[10] C. M. Kirsch and A. Sokolova, “The logical execution time paradigm,” in Advances in Real-Time Systems. Springer, 2012, pp. 103–120.

[11] A. Benveniste and G. Berry, “The synchronous approach to reactive and real-time systems,” Proceedings of the IEEE, vol. 79, no. 9, pp. 1270–1282, 1991.

[12] E. A. Lee, J. Liu, L. Muljadi, and H. Zheng, “Discrete-event models,” in System Design, Modeling, and Simulation using Ptolemy II, C. Ptolemaeus, Ed. Ptolemy.org, 2014.

[13] B. P. Zeigler, Y. Moon, D. Kim, and G. Ball, “The devs environment for high-performance modeling and simulation,” IEEE Computational Science and Engineering, vol. 4, no. 3, pp. 61–71, 1997.

[14] S. Liao, S. Tjiang, and R. Gupta, “An efficient implementation of reactivity for modeling hardware in the Scenic design environment,” in Design Automation Conference. ACM, Inc., 1997, Conference Proceedings.

[15] L. Lo Bello and W. Steiner, “A perspective on ieee time-sensitive networking for industrial communication and automation systems,” in Proceedings of the IEEE, vol. 1094–1120, 2019.

[16] E. Brewer, “CAP twelve years later: How the "rules" have changed,” IEEE Computer, vol. 45, no. 2, pp. 23–29, February 2012.

[17] Y. Zhao, E. A. Lee, and J. Liu, “A programming model for time-synchronized distributed real-time systems,” in Real-Time and Embedded Technology and Applications Symposium (RTAS). IEEE, 2007, Conference Proceedings, pp. 259 – 268.

[18] J. C. Corbett, J. Dean, M. Epstein, A. Fikes, C. Frost, J. Furman, S. Ghemawat, A. Gubarev, C. Heiser, P. Hochschild, W. Hsieh, S. Kanthak, E. Kogan, H. Li, A. Lloyd, S. Melnik, D. Mwaura, D. Nagle, S. Quinlan, R. Rao, L. Rolig, Y. Saito, M. Szymaniak, C. Taylor, R. Wang, and D. Woodford, “Spanner: Google’s globally-distributed database,” in OSDI, 2012, Conference Proceedings.

[19] L. Lamport, “Using time instead of timeout for fault-tolerant distributed systems,” ACM Transactions on Programming Languages and Systems, vol. 6, no. 2, pp. 254–280, 1984.

[20] K. M. Chandy and J. Misra, “Distributed simulation: A case study in design and verification of distributed programs,” IEEE Trans. on Software Engineering, vol. 5, no. 4, pp. 440–452, 1979.

[21] J. Misra, “Distributed discrete event simulation,” ACM Computing Surveys, vol. 18, no. 1, pp. 39–65, 1986.

[22] J. S. Dahmann, R. M. Fujimoto, and R. M. Weatherly, “The department of defense high level architecture,” in Proceedings of the 29th conference on Winter simulation, 1997, pp. 142–149.

[23] D. Thomas, W. Woodall, and E. Fernandez, “Next-generation ROS: Building on DDS,” in ROSCon Chicago 2014. Mountain View, CA: Open Robotics, sep 2014. [Online]. Available: https://vimeo.com/106992622

[24] O. Standard, “MQTT Version 5.0,” Retrieved June, vol. 22, p. 2020, 2019.

[25] M. Lohstroh, Í. Íñar Romero, A. Goens, P. Derler, J. Castrillón, E. A. Lee, and A. Sangiovanni-Vincentelli, “Reactors: A deterministic model for composable reactive systems,” in 8th International Workshop on Model-Based Design of Cyber Physical Systems (CyPhy’19), vol. LNCS 11971. Springer-Verlag, 2019, Conference Proceedings, p. 27.

[26] Z. Manna and A. Pnueli, “Verifying hybrid systems,” in Hybrid Systems, vol. LNCS 736, 1993, Conference Proceedings, pp. 4–35.

[27] C. Rosenthal and N. Jones, Chaos engineering. O’Reilly Media, Incorporated, 2020, vol. 1005.

[28] T. Foote, “tf: The transform library,” in 2013 IEEE Conference on Technologies for Practical Robot Applications (TePRA), 2013, pp. 1–6.

[29] G. Lütgten and V. Carreno, “Analyzing mode confusion via model checking,” in International SPIN Workshop on Model Checking of Software. Springer, 1999, pp. 120–135.

[30] J. Zou, S. Matic, E. A. Lee, T. H. Feng, and P. Derler, “Execution strategies for Prides, a programming model for distributed embedded systems,” in Real-Time and Embedded Technology and Applications Symposium (RTAS). IEEE, 2009, Conference Proceedings.

[31] F. Baccelli, G. Cohen, G. J. Olster, and J. P. Quadrat, Synchronization and Linearity, An Algebra for Discrete Event Systems. New York: Wiley, 1992.

[32] J. C. Eidson, Measurement, Control, and Communication Using IEEE 1588. Springer, 2006.

[33] J. C. Eidson and K. B. Stanton, “Timing in cyber-physical systems: the last inch problem,” in IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS). IEEE, 2015, Conference Proceedings, pp. 19–24.

[34] Y. Geng, S. Liu, Z. Yin, A. Naik, B. Prabhakar, M. Rosenblum, and A. Vahdat, “Exploiting a natural network effect for scalable, fine-grained clock synchronization,” in 15th USENIX Symposium on Networked Systems Design and Implementation (NSDI 18), 2018, pp. 81–94.

[35] P. E. Black et al., Dictionary of algorithms and data structures. Addison-Wesley, 1998.

[36] D. Merkel et al., “Docker: lightweight linux containers for consistent development and deployment.” Linux journal, vol. 2014, no. 239, p. 2, 2014.

[37] E. A. Lee and M. Lohstroh, “Time for all programs, not just real-time programs,” in International Symposium on Leveraging Applications of Formal Methods (ISoLA 2021), Springer, 2021, pp. 213–232.

[38] D. Jefferson, “Virtual time.” ACM Trans. Programming Languages and Systems, vol. 7, no. 3, pp. 404–425, 1985.
[39] G. Baudart, A. Benveniste, and T. Bourke, “Loosely time-triggered architectures: improvements and comparisons,” *ACM Transactions on Embedded Computing Systems (TECS)*, vol. 15, no. 4, pp. 1–26, 2016.

[40] S. Tripakis, C. Pinello, A. Benveniste, S.-V. A., P. Caspi, and M. Di Natale, “Implementing synchronous models on loosely time triggered architectures,” *IEEE Transactions on Computers*, vol. 57, no. 10, pp. 1300–1314, 2008.

[41] H. Kopetz and G. Bauer, “The time-triggered architecture.” *Proceedings of the IEEE*, vol. 91, no. 1, pp. 112–126, 2003.

[42] R. Ernst, L. Ahrendts, and K.-B. Gemlau, “System level let: Mastering cause-effect chains in distributed systems,” in *IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2018, pp. 4084–4089.

[43] J.-B. Chaudron, D. Saussié, P. Siron, and M. Adelantado, “Real-time distributed simulations in an hla framework: Application to aircraft simulation,” *Simulation*, vol. 90, no. 6, pp. 627–643, 2014.

[44] J. Cardoso and P. Siron, “Ptolemy-hla: A cyber-physical system distributed simulation framework,” in *Principles of Modeling*. Springer, 2018, pp. 122–142.

[45] B. Wan, H. Luo, K. Zhou, X. Li, C. Wang, X. Chen, and X. Zhou, “A time-aware programming framework for constructing predictable real-time systems,” in *2017 IEEE 19th International Conference on High Performance Computing and Communications; IEEE 15th International Conference on Smart City; IEEE 3rd International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*. IEEE, 2017, pp. 578–585.

[46] W. Baron, A. Arestova, C. Sippl, K.-S. Hielscher, and R. German, “Lett: An execution model for distributed real-time systems,” in *2021 IEEE 94th Vehicular Technology Conference (VTC2021-Fall)*. IEEE, 2021, pp. 1–7.

[47] C. Menard, A. Goens, M. Lohstroh, and J. Castrillon, “Achieving determinism in adaptive AUTOSAR,” in *Design, Automation and Test in Europe (DATE 20)*, Grenoble, France, March 2020.

[48] S. Fürst, J. Mössinger, S. Buzzel, T. Weber, F. Kirschke-Biller, P. Heitkämper, G. Kinkelín, K. Nishikawa, and K. Lange, “Autosar—a worldwide standard is on the road,” in *14th International VDI Congress Electronic Systems for Vehicles*, Baden-Baden, vol. 62, 2009, p. 5.