Redundancy Overview

Redundant systems and components guard against any single hardware or software failure. Redundancy relies on the probability that two failures within a short duration are highly improbable. With critical systems, controller redundancy alone is insufficient. A fully redundant system requires end-to-end redundancy, system isolation to avoid the effects of a cascading fault, and failure detection of any critical component. This means all system components, including the network, must be redundant and actively monitored so the Mean Time To Repair (MTTR) of any single component is minimized. Failing to detect and repair even a fault in a backup component allows the system to effectively operate in a non-redundant mode (referred to as ‘simplex’ operation) until an inevitable failure of a primary component occurs, leaving the system with no fallback position to continue operating correctly.

A Redundant Logical Controller is typically made up of two or more physical controllers and defined by their Role plus their State. The physical controllers are often designated the roles of Primary and Secondaries (or backups), where the Primary controller outputs are used to drive the system, and the Backup stands ready to take over as Primary in the event of a failure. By definition, the Primary is in the Active State, indicating it is operational and driving the system. Each of the Backup controllers can be in any one of the following states: Cold/Warm-Standby or Hot-standby. Hot-standby designates that the switchover of the Active role from Primary to Backup is the time to detect the Primary has failed (that is, the Backup has all the state necessary to take over as Primary.) Cold and Warm-Standby may require a lag to gain sufficient state to take over as the Primary. The method employed is dependent upon the system redundancy switchover requirements.

Redundancy In a DDS Shipboard System

Shown in the figure below is an example of a Redundant Shipboard Navigation System.

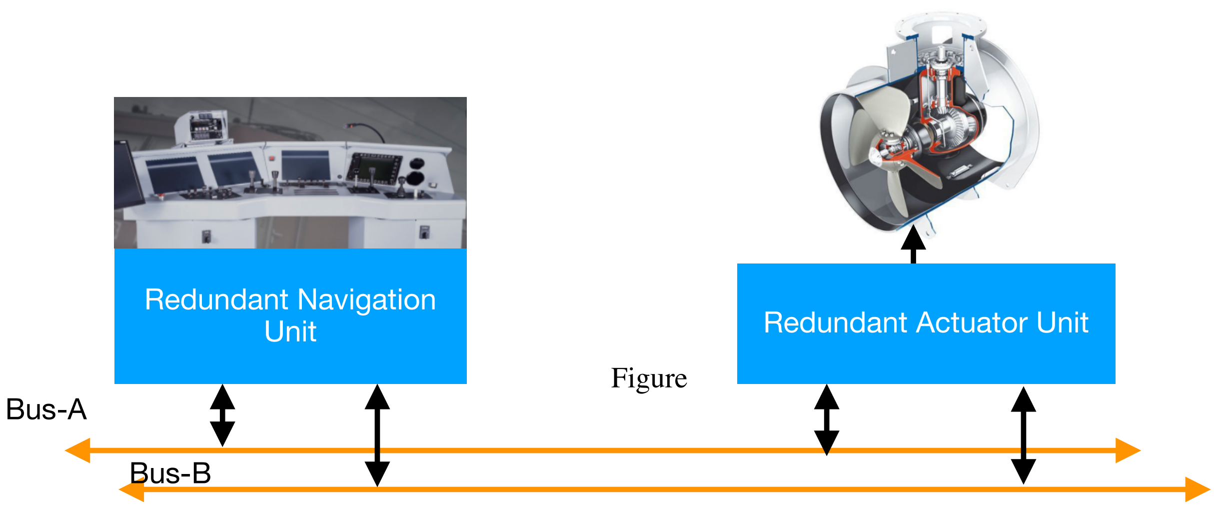


Figure 1 - Basic Architecture of an End-to-End Redundant Shipboard Navigation System

In a fully redundant system, more than one actuator (propeller) shares the load. In the event of a failure, the other actuators compensate for the lost actuator.

There are multiple approaches to providing redundancy. This document presents three redundancy architectures[1], specifically in the context of a ship's thrust/steerage control system using DDS. (1) A Simple Duplex Architecture (see Figure 2 below), utilizing a Primary and Standby Controller, whereupon the Primary failing, the Standby takes over. (2) A Custom Hardware Duplex Redundancy Architecture (same Figure 2 below) presenting a logical controller comprised of two controllers, each with two processors. Here, neither controller is designated Primary or Secondary, as both drive the system simultaneously. In the event that the two processors on either controller disagree, that controller would remove itself from the system (leaving the remaining controller to continue to drive the bus and alarm the failure). (3) a 3-way Voting design (see Figure 4 below) where the logical controller is comprised of three simplex controllers. Using Heartbeat messages and a common algorithm, such as the lowest BoardId and each board's state, the Active Controller is voted by two of the three controllers. Upon any controller failure, the two remaining controllers would, by algorithm, select the Active controller. The remaining controllers would be responsible for alarming and identifying any failed controllers.

Below, we discuss each of these utilizing DDS where applicable.

Simple Duplex Redundancy

A simple Duplex architecture utilizes two off-the-shelf controllers statically designated Primary and Secondary. Health monitoring is done with either a heartbeat or using DDS Liveliness Quality of Service (QoS) so that each controller can detect and alarm the loss of the other. DDS Exclusive Ownership QoS allows the Primary's data, with higher Ownership Strength, to be passed by DDS to the receiving controller application[2]. A deadline QoS or loss of Liveliness will cause DDS to switch over to the Secondary Controller. The active controller is responsible for alarming the system of a failed partner controller to minimize MTTR and ensure continued redundancy. Both controllers receive and process data in relative synchronization. Upon the Primary returning to service, DDS will instantly resume utilization of the restored Primary's data based on the higher Exclusive Ownership Strength. This approach, while simple, assumes the mode of failure is catastrophic (i.e., the process or controller completely fails) and not oscillatory (i.e., the controller does not bounce up and down). It does not cover more subtle issues of software bugs where both controllers are sending different results, and the Primary is incorrect.

To achieve end-to-end redundancy, each controller would run a Network Alarm Participant (NAP) to independently monitor network heartbeats between controllers of each assigned bus to ensure a failure on either bus is alarmed for immediate repair (see Detect Network Failures - Alarm and Clear below). Independent of alarming, the design might use Connext's Interface Priority feature to change interfaces associated with each bus upon a failure.

"Enhancement Options" Discussion

1. Stronger Ownership Strength value for a Secondary taking over. Upon the Secondary taking over, it would change its ownership strength to a value greater than the Primary's strength. That is, there are three ownership strengths: Default Value Primary(High), Default Value Secondary (Lowest), and Take-over Value Secondary (Highest). This guards against a Primary failing but continuing to send data (so called Zombie process). Upon the Primary being restored to service, the secondary would again lower its ownership to the initial Value Secondary. Drawbacks with this approach are that the secondary could fail, believing the Primary failed and raising its ownership strength and taking over, when it is in fact the failing component (bottom line, with two controllers, there is no way under conflicting circumstances to know who is correct and who is failed.) This option attempts to guard against "the most likely" fault scenario.

---

[1] We won't discuss so-called n+1 redundancy where you have multiple controllers or devices active, perhaps load sharing, with one or more standby units in reserve.

[2] An application is the software on the controller that performs the required function (e.g., thrust / actuator activity.)

2. Add Explicit Application Level Acknowledgment (EAA) to the Tracker_HB (Heartbeat) Topic. The idea is that EAA can help guard against a "zombied" process (i.e., a process that is not working but continues to send Tracker_HBs). There are a couple of issues using this mechanism for this use case. Firstly, the HBs run full duplex, so if you are worried about an application being a zombie, you can put application-level consistency checks in the HB writer logic vs. the Application Level Acknowledgment. Secondly, it does not work for this application due to common instance resource blocking.) EAA requires making the Tracker_HB topics reliable (not for Reliability's sake, but for its own sake. It also requires KEEP_ALL History with appropriate resource limits. HBs are already periodic and not critical, so you make them Reliable to add EAA). Trackers each send heartbeats to the two other trackers as an instance key'd on their writer GUID. This is how trackers discover each other. While each Tracker_HB reader receives the two instances of the other trackers (they don't receive their own heartbeat), each tracker writes only one instance to the other two trackers. If a tracker disappears, ALL heartbeats from each tracker writer will block, causing all heartbeats in the system to stop and cascading the fault. My takeaway is that EAA adds value for one-way (simplex) topic writing to readers where a) you want Reliability, and b) you don't have a full duplex path.

Custom Hardware Duplex Redundancy

A Duplex Redundancy design, using specialized lockstep hardware, contains two statically designated controllers with no distinction of Role (Primary and Secondary) or state (Active and Standby). Each controller has two processors running identical applications receiving and calculating the same information in lockstep. All four processors (two on each controller) should have identical outputs clock-to-clock. On any one controller, if lockstep output data does not match, specialized hardware on the controller disconnects the controller from the data bus. Software on each controller can also run consistency checks and remove itself from the data bus if any data is found inconsistent. The remaining operational controller can then alarm the system of the failure. Once the failed controller is restored, it will return to synchronously providing outbound data.

As in the Simple Duplex Architecture, each controller would run a Network Alarm Participant (NAP) to monitor and alarm a network failure independently.

While a Custom Hardware Duplex Redundancy Architecture, as described here, can be very fast at switching over, it has three deficiencies. 1. Due to the required custom hardware; it is expensive. 2) Because all processors must run the exact same software to stay in lockstep, it is vulnerable to an application bug[3] (i.e., A flawed application will happily run on all four processors without detection.), and 3) Because of the lockstep requirement, both controllers must be physically next to each other and are susceptible to localized physical damage (e.g., flooding, fire, or explosives).

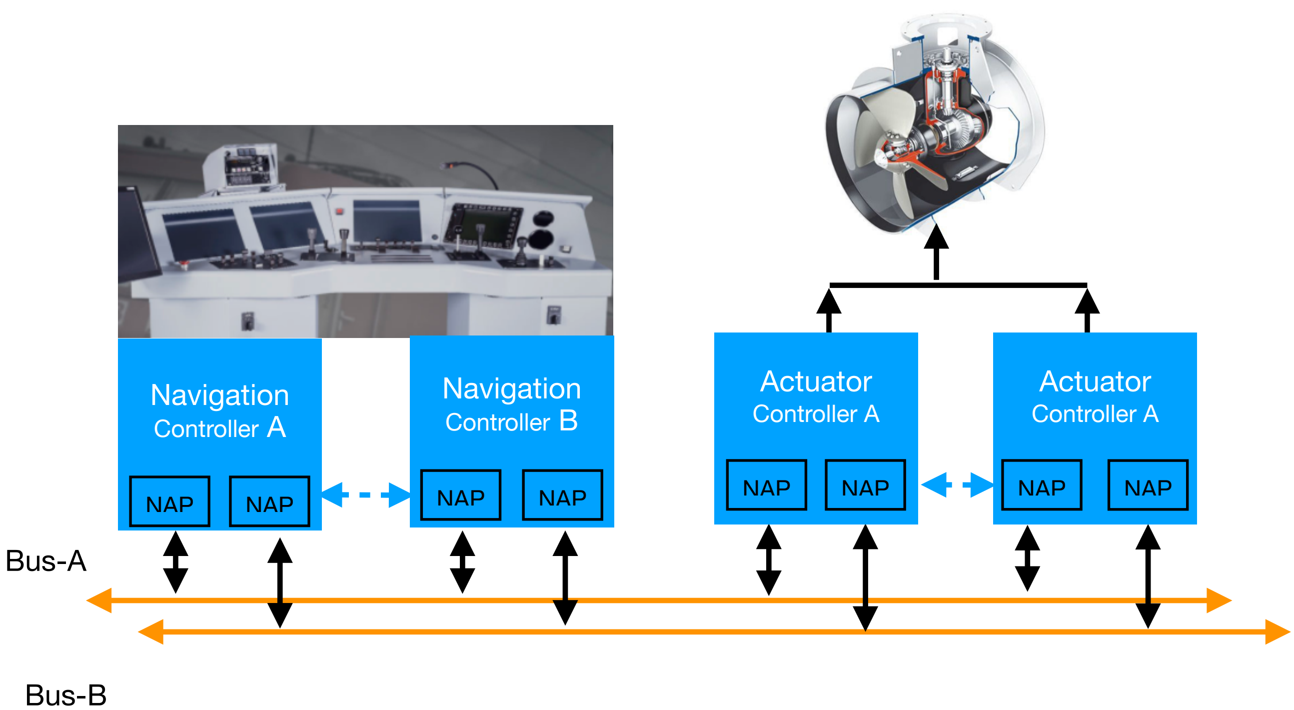


Figure 2 - Duplex Architecture

[3] Machines using this architecture typically were used for On-Line Transactional Processing (OLTP) and had special OS level Check-pointing to ensure each transaction was preserved and recoverable.

Three-way voting Redundancy

With a Three-way voting design, each logical controller unit is made up of three off-the-shelf controller components (denoted by the orange circle in the figure below). Each Controller will vote and is voted a role of Primary, Secondary, or Tertiary. The Primary will drive the system, with the Secondary and Tertiary standing ready to take over. Technically, unless there is a double fault, the Tertiary would never drive the system and is used to validate a majority vote.

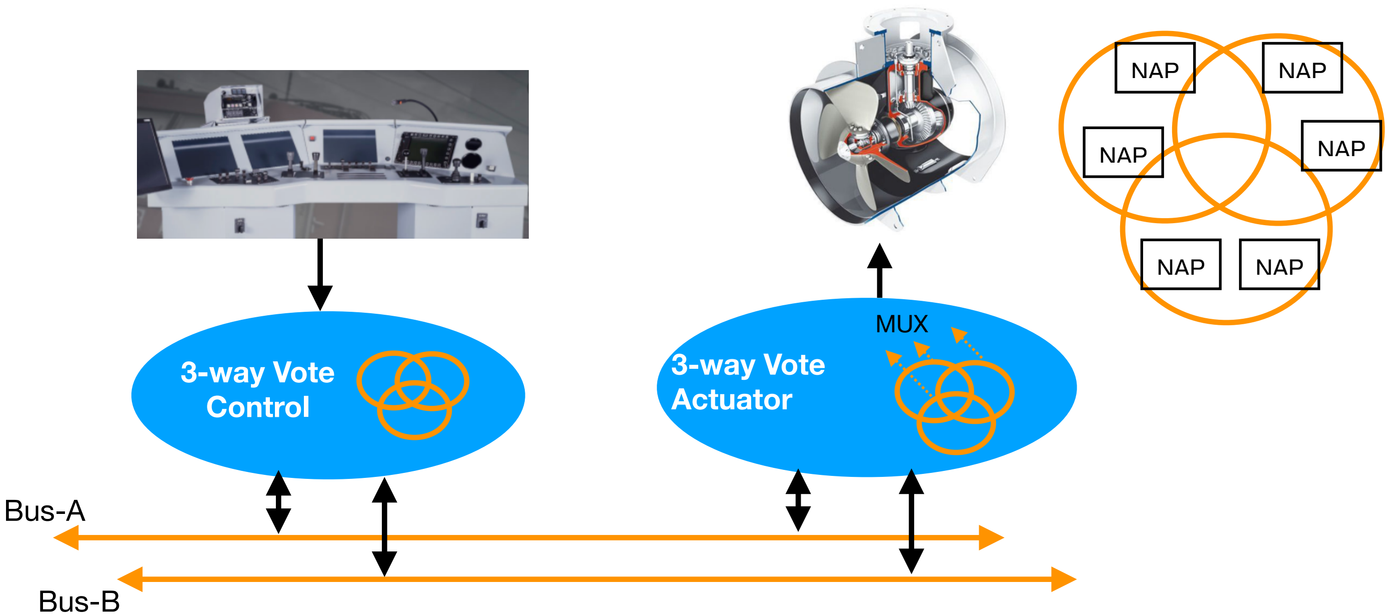


Figure 3 - Three-way Voting Architecture

Using heartbeat messages or DDS Liveliness QoS, each controller can monitor the health of the other two controllers. A voting algorithm is used to determine which of the operating controllers would be the primary and which are backups. Like the duplex design, each of the controller components would execute application processes and run a NAP on each interface to detect and alarm for a Network failure. Independent of the NAP, the applications could use Connext Interface Priority to switch from one network to the other upon failure. Each controller effectively maintains a distributed redundancy database of controllers in or out of service (or failed). Like the Simple Duplex Architecture described above, Exclusive Ownership and Ownership strength QoS is used. Here, each the Primary, Secondary, and Tertiary would drive the data at lower Ownership Strength relative to their role. Roles could initially be selected based on an algorithm such as the lowest DDS Global Unique IDentifier (GUID). To prevent “Role Oscillation,” Once a role is selected, it should be maintained unless the controller with that role fails. In this case, all controllers with lower roles would be promoted. This requires a dynamic change in Ownership Strength. A failed controller that was replaced or returned to service would come into the system in the lowest available role. This is usually Tertiary unless the system has incurred a double fault and is running with just the Primary Controller.

Three-way Voting has the advantage of using off-the-shelf hardware while achieving a relatively quick switchover time (using DDS Deadline or Liveliness QoS, which could be set on the order of milliseconds) and, via Dynamic Ownership, can avoid “Controller Role Oscillation.”

Additionally, extensions to the Three-way Voting implementation for hyper-critical applications, such as NASA manned spacecraft, could include: (1) Because the control application is not lock-stepped, it could be written by different vendors, making it highly unlikely that any two systems would fail at the same time. This allows the failed application to be taken out of service and rebooted to return to service in a lower role. (2) Rather than using Exclusive Ownership and voting for a role, each ”command sample” (e.g., Thrust Control) could be sent from each controller as an instance where the receiving application - e.g., Thrust Control Application, selects the best two or three command instances and alarms any dissenting command source.

Redundancy Layer (RL) using DDS

To isolate and abstract the application from a particular redundancy implementation, we introduce a Redundancy Layer (RL). The RL is responsible for the following activities: 1) Active / Standby state selection, 2) failure detection and alarm, and 3) switchover selection. A single API is presented to the application, minimizing exposure of the redundancy implementation. In a distributed system, the RL is also responsible for monitoring and alarming a network failure.
For a shipboard system, both the Redundant Navigation Unit Controller and the Redundant Actuator Controller could use the same Redundancy Layer.

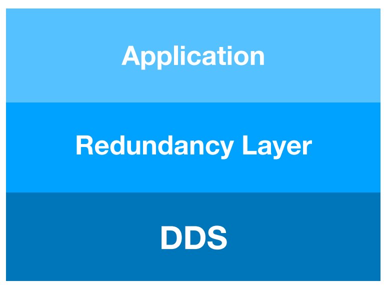


Figure 4 - Redundancy Abstraction Layer

Let’s look at these responsibilities in detail in the context of our distributed shipboard system, as shown in Figure 4 above. Most of this discussion, with the exception of network monitoring, applies only to the Three-Way Voting design since the Duplex design is mostly hardware-based and has no Active / Standby role distinction.

Active Controller Selection Process and Controller Alarms:

All like redundant controllers (Navigation or Actuators) will initialize to the highest Standby state possible and send and receive some sort of Redundancy Layer Controller Heartbeat (RLCHB) between themselves. They will then enter the voting cycle as described in the next paragraph. The RLCHB is used to establish that the controller is alive and learn which controllers are capable of going to the Active state. The RLCHB topic should contain the source Controller ID and its current state. The RLCHB is sent periodically with QoS of Best Effort, along with a deadline, since we want to notice any failure and not have the heartbeat retried.

Each Active capable (meaning Hot-Standby) controller, after waiting two times the RLCHB time, will send a VoteControllerState topic, listing its nomination, based on a common algorithm (e.g., lowest Controller ID) of potential Active, Standby1, and Standby2 (if applicable) state. Precedence should be given to any currently Active Controller to avoid unnecessary Active/Standby switching. Each capable controller, using its own vote and achieving two votes in agreement for a role, will take on that role, reflecting it in the next RLCHB it sends out. Note that votes should be unanimous, and any minority vote from a controller indicates the controller is faulted. The VoteControllerState topic is sent with QoS of Transient Local Durability to allow a late joining controller to assess the existing system priority and its entry role.

Each controller will reenter the voting cycle anytime it fails to receive RLCHB from any controller to re-establish controller roles per the voting algorithm. In the case of an Active Controller failure, this could occur either from an Active Controller failure or a Standby controller communications link failure (network or onboard transceiver). With Redundant networks, if the failure was due to a communications link, only one controller would attempt an updated vote, which would be inconsistent with the other two controllers, alerting the Active Controller of the need to Alarm the system. In the case where the Active Controller's transceiver fails, and its RLCHBs are not received from either the standby, while the Active Controller will remain "Active" locally, it is isolated from the system, and the Newly voted Active Controller will take precedence.

The remaining majority of controllers will always alarm or clear any failed/recovered controller(s) Alarms. Each controller "user data" (e.g., commands to navigate the ship) should set its exclusive ownership strength relative to its role (Active, Standby-One, and Standby-two in decreasing strength) so that only the Active controller "user data" output will be seen by the system.

Detect Network Failures - Alarm and Clear

Connext DDS 7.2 offers multiple interface prioritization. This means that the user can specify two interfaces in priority order; in the event one fails, the other will take over automatically. This ensures that messages are reliably sent exactly once, even through a switchover. There are two limitations with this solution that need to be addressed.

1. An interface is an IP address and not necessarily a different network. So, the user has to configure IP addresses or ensure each interface corresponds to a different physical network.
2. While Connext detects failure of the active network (Primary), it does not continually check that the backup network has failed (perhaps long ago).

To ensure the backup network is available, a Network Alarm Participant (NAP) (i.e., a separate Connext Application) would need to be run minimally twice (one for each network) between 'like' controllers, sending what we'll call Redundancy Layer Network Heartbeats (RLNHB), between them (Bidirectionally on each interface). Upon an appropriate DDS Deadline miss event, a Network Alarm would be raised. This would ensure the user is notified of a network failure.

The table below shows the logical conclusion based on the Network Alarm Topic state.

Note: NAPs send data between only Like controllers on each respective network, i.e., NavCtrlrP on N1 would send to
NavCtrlrS-N1 etc.

Nav Ctrlr P-N1	Nav Ctrlr P-N2	Nav Ctrlr S-N1	Nav Ctrlr S-N2	Actuator Ctrlr P-N1	Actuator Ctrlr P-N2	Actuator Ctrlr S-N1	Actuator Ctrlr S-N2	FAULT
Good	Good	Good	Good	Good	Good	Good	Good#	None
Good	Good	Good	Good	Good	Good	Good	Fail #**	Actuator Ctrl P-N2 Fail or Actuator Ctrl S-N2**
Good	Good	Good	Good	Fail	Fail	Fail	Fail	Either Actuator Ctrlr P or S Down ##

Nav Ctrlr P-N1	Nav Ctrlr P-N2	Nav Ctrlr S-N1	Nav Ctrlr S-N2	Actuator Ctrlr P-N1	Actuator Ctrlr P-N2	Actuator Ctrlr S-N1	Actuator Ctrlr S-N2	FAULT
Fail	Fail	Fail	Fail	Good	Good	Good	Good	Either Nav Controller P or S Down##
Fail	Good	Fail	Good	Fail	Good	Fail	Good	Network1 Failure
Good	Fail	Good	Fail	Good	Fail	Good	Fail	Network2 Failure
Fail	Fail	Fail	Fail	Fail	Fail	Fail	Fail	Double Fault - Both Networks Fail

* P-N1, S-N2 etc is the 'Like Controller' Primary/Secondary Role, and Network interface (N1 or N2).
# Good means RLNHB received, Fail means RLNHB not received on the interface
** Any Single failure indicates the Actuator either the driver on the sending controller failed or receiver on receiving controller failed (to keep the table simple, we won't expand all eight scenarios out)
This condition is directly detected by the RLCHB so no alarm should be raised by the Network Alarm Participant(NAP).
This table shows only two controllers of like types, and technically all that's needed to run NAPs on both networks. However to detect transceiver failures on any controller, NAPs should be run on all like controllers (i.e. all three in the case of three-way voting).

Each NAP will raise an alarm for any detected Failure. However, each NAP will subscribe to all Like Controller RLNHBs to actually conclude a network alarm or transceiver / Controller fault (Red Faults above) which is not detectable using RLCHBs. The NAP should not raise failed Controller Alarms (Yellow Faults), as those are handled directly by the controller using RLCHBs.

Topic	Qos	Type	Written by	Read by
RLCHB	Best effort,	Periodic	All RLs	All RLs
RLNHB	Best effort,	Periodic	All NAP applications	All NAP applications
Vote	Reliable	As Needed	All RLs	All RLs
Controller Alarm	Reliable	As Needed	Network Alarm Participant	Network Alarm Participant
Network Alarm	Reliable	As Needed	Network Alarm Participant	Network Alarm Participant

Summary of Reliability LayerNew Topics

Conclusion

While a 3-way voting redundancy has the slightly increased cost of an additional off-the-shelf controller as well as increased software complexity over a Duplex architecture, it meets the full requirements of ‘no single point of failure, including not only a physical event such as fire, flood, or explosion which could impact a Hardware Duplex approach, but also guard against software issues. The table below highlights the advantages and disadvantages of each redundancy approach.

Redundancy Architecture	Cost	Complexity	Detect and overcome Hardware Failure	Detect and overcome a Software bug	Distributed (not susceptible to local event)
Simple Duplex	Lowest	Low	Yes	No	Yes
Custom Hardware Duplex	High	High*	Yes	No	No
Three-way	Low	Low-high**	Yes	Yes	Yes

* Hardware complexity very high, software complexity is low
** requires Redundancy Layer (available on Github) for base controller role voting - (hyper critical applications), three different application implementations to detect software issues with optional receiver application applying vote selection to three received sample instances.

Pixytracker App Demo - Three-way Voting

For Demonstration purposes, just the Pixytracker App portion of the Pixytracker system (shown below) will be made redundant using the Three-way Voting Architecture described above. This will require moving the tracker app from a Mac-based host to three Raspberry Pi 3B+ single-board computers. This demo WILL NOT run on duplicate networks ("The network is not the adversary.") or duplicate Pixycam apps.

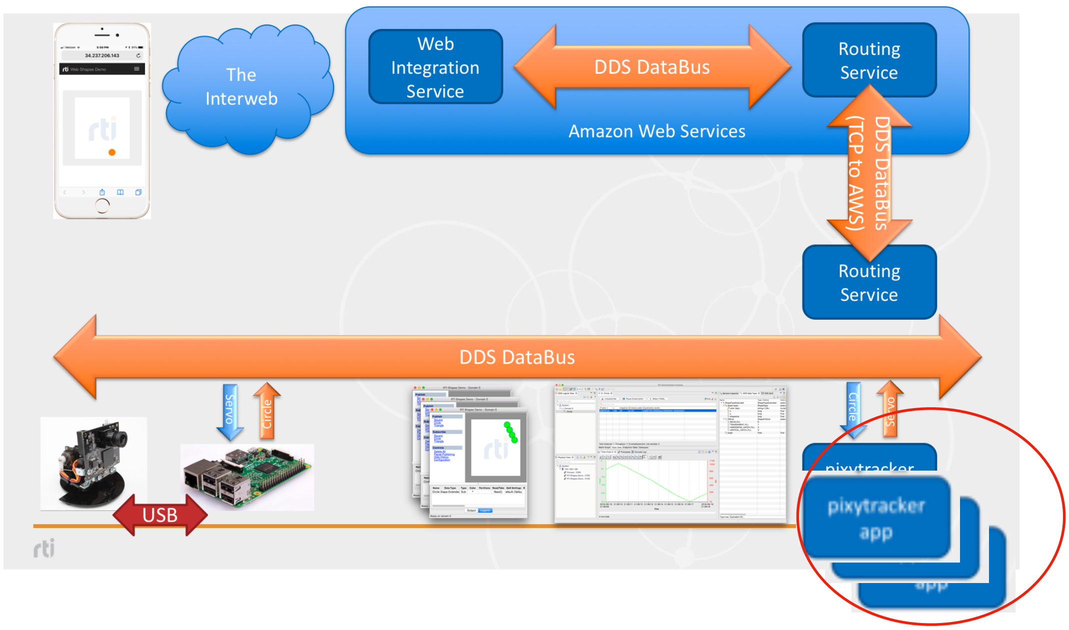


Figure 5 Pixytracker application w/3-way Voting logic

The demo will first bring up one RPi running the tracker app. Upon rebooting the Raspberry, we can show no tracking takes place while the Raspberry is offline. We'll then bring up three Raspberrys showing that bouncing any one of the Raspberry's causes no perceivable change in pixy cam tracking. A set of status LEDs will connected to the gpio pins on the pi and will provide status and role information of system (see LED operation below).

Modification to PixyShapes.cxx (app on the Raspberry)

Because we are only protecting the Pixytracker app and not detecting network failure or pixy cam failure - only QoS settings to enable ownership strength on the pixy/servo_control topic need be modified (with Reliable Reliability with Deadline 200ms.). No code modifications should be required of the pixyShapes code.

Modifications to PixyTracker.cxx to make it redundancy (3-way voting) capable

Existing Topics (and Modifications):

Circle (No changes)

Pixy/servo_control (Changes)
Data_reader: N

Data_writer: Y

Changes: QoS Only: Enable Ownership Strength (and Reliable Reliability with Deadline 100ms.) Each PixyTracker Controller will associate a unique strength with it's voted Role.

Redundancy Layer New Topic Definitions

New Topics:
RLCHB - best effort/periodic four times per second (Voting time < 3 seconds) - contains the senders participant *Keyed* GUID for algorithm comparison. This topic will have a deadline of 2x its send rate.

Vote topic - sent durably by each controller. Contains senders GUID (Keyed) along with its vote of who (GUIDS) is the primary controller (GUID) followed by vote of Controller Relative Number 1, 2, 3 (lowest GUID to highest).

Tracker Ordinal Number (1-3) is used locally to identify itself and the LED position (see below) as described below in LED Operation. A controllers Relative number can change, however, the actual Primary Controller will not change unless it fails (I.e. hysteresis so we don't oscillate between primary controllers).

Voting Algorithm -

The voting algorithm will select Primary, Secondary, and Tertiary controllers (Trackers). Each controller will set the Ownership Strength of the Pixy/Servo topic relative to its role as follows: Primary (30), Secondary (20), Tertiary (10).

Upon a controller initializing, a controller will come up in one of two scenarios: 1) As part of a new system coming online (i.e., no controllers were previously running, no rolls have been established, and 2) As a late Joiner to an existing system. For each of these scenarios, the algorithm will work as follows:

System Initialization: Controllers will be assigned roles according to their GUID. The Primary is assigned to the lowest GUID, Secondary to the second lowest, and Tertiary to the highest GUID.

While the system is designed to work with three controllers, it should work independently of Fault Tolerance with one or two controllers. Any late joining controllers always come in at the next available highest role. I.e., A single controller as Primary, with subsequent controllers coming in as Secondary and Tertiary. Two controllers coming up at the same time (within 10 seconds of each other) will come up as Primary and Secondary based on GUID value.

To allow "Initialization Time" as controllers come up within ten seconds of each other, they will wait for either ten seconds from the last controller that was recognized (via Heartbeat messages) or three controllers. Once the "Initialization Time" is concluded, each controller will cast a vote for Primary, Secondary, and Tertiary. The controller with the greatest number of votes for each roll will be assigned that roll. Note: All controllers should have a common view, so all voting should be unanimous for each roll. In the event of a non-unanimous vote, the source GUID of the minority vote should be marked FAILED.

Late Joiner: To avoid Oscillation, a controller, once a Primary, should remain in that role as other controllers come and go unless it is the controller that fails. The same is true of the Secondary if there is a Primary; that is, any third controller will come in as Tertiary. Should a controller fail, other controllers will be 'Promoted' to the next highest roll (e.g., A Primary failure causes both the Secondary and Tertiary to each be promoted to Primary and Secondary, and a Secondary failure will cause the Tertiary to be promoted to Secondary. Late Joiners always come in at the lowest available role.

A controller is able to make a distinction as to which scenario it is in based on receiving a vote prior to reaching the Voting State. Votes are durable, so receiving a vote prior indicates the control is a Late Joiner to a running system. Receiving votes after the Vote state indicates a controller is in the System Initialization scenario. NOTE: To be deterministic, all controllers must either wait until they see three unique heartbeats (i.e., three controllers) or ten seconds after the last unique heartbeat. This ensures all controllers depart the "Initialization Time" within 100ms of each other (and will not receive another controller's vote in this phase unless it is a Late Joiner.)

No Pixy/Servo topics should be written until a Primary has been selected and a controller has established its own role.

Additional controllers beyond three will be ignored.

Voted Result (non-topic):

Depending on how paranoid we are, a separate Vote Result announcement topic could be published durably by the Primary Controller. However, this design will allow the durable Voting topic to suffice. Any unit that does not agree with the two votes of the other controllers will take itself offline and/or restart. This ensures that the Vote Topic essentially reflects any voting result topic.

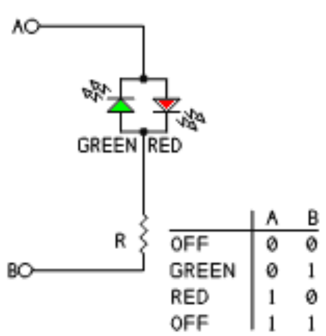
ReVoting - Revoting will occur anytime a tracker is removed or added (or comes back into operation). Ideally, we'd trigger on a deadline miss and identify the lost writer (Tracker). We need the instance of the HB writer that missed its deadline so we can clear out the database (RedundancyInfo) for that writer and revote. Instead, we'll run the SM at 1 second and the HB rate at 250ms. A deadman count will be employed. Each HB will increment an internal count (kept in the RedundancyInfo struct.) When the state machine is in STEADY_STATE, it will check the count for non-zero and then clear this count. The corresponding Tracker will be nulled out of the RedundancyInfo struct, and the SM will revert to the VOTE state. During this time, if the primary had failed, the secondary will be driving the servo topic (the servo topic has ownership strength with a 100ms deadline)

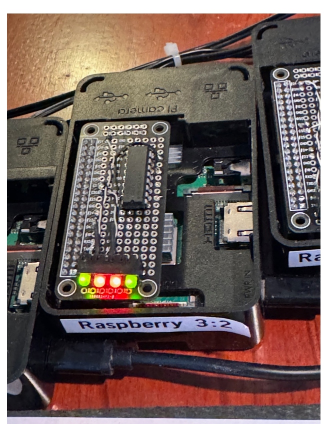
LED Operation:

Each Controller will have four red/green LEDs assigned as follows:

ROLE			STATUS
LED1	**LED2**	**LED3**	**LED4**
Primary	Secondary	Tertiary	OK/Fail

Each LED is wired to two GPIO pins as defined in led.hpp as follows. Where R=470ohms (1 resistor of 8 of the DIP resistor array shown in the photo and called out below). Note - Some of the black Pi case will need to be trimmed to allow room for the 40 pin header, as well allow the Pi-hat to fit flush. Also DO NOT place the LED array in the two front thru-hole rows on either end of the Pi-hat board (these are unused power rails and are shorted together, also the LED array pin pitch is different than the pitch of these power rails). Use the first row of thru-holes in the main "grid" where the resistor array is mounted.





Component	Source	QTY	Price	Ext Price
Pi Hat Prototype PCB (pkg of 3) (half size for Raspberry Pi Zero)	Amazon	1	$13.99	$13.99
Quad LED Array (red/green)	Digikey	3	8.53	25.59
40 Pin Header - through hole (used to connect Pi-hat to Pi to get extra height needed)	Digikey	3	1.96	5.88
470 ohm Isolated Resistor Array	Avnet	3	0.98	2.94
Misc Wire				
Misc Solder				
TOTAL				**$48.40**

Each Tracker working tracker will present a Green LED indicating its role.
A Red LED will indicate a failed unit and role. Off indicates a Tracker with a corresponding back up role is Operational.

LED4 will indicate the Trackers Own status and is redundant with the ROLE Status but helpful upon initialization prior to roles being assigned and if the trackers software detects its own failure.

Note: corresponding messages will be printed on the controller console indicating each controllers Relative Number, and who is primary.

PixyTracker Code Modifications

Expected Behavior

Upon startup, a system will wait a ten-second grace period to allow all controllers to boot up. Depending upon the number of detected controllers, enter one of the described three states above and be deemed operational. During this operational phase, the system may degrade to a lower redundancy state or upgrade to a higher redundancy state sending the appropriate alarms and informational messages as described previously. It is up to the operator to take action to minimize MTTR and maintain the highest availability.

All active controllers publish Servo control topics in response to filtered (YELLOW) Circle topics sent by the pixyshapes application to the pixytrackers. Circle Shapes topics may not be regular or periodic.

At least one controller should be sending pixy/servo_updates and possibly two or all three. In the latter cases, the units should not be in simplex mode, but all three should agree they are in 3-way voting mode. In either case, only the pixy/servo_control topic with the highest ownership will be forwarded by DDS to the pixy cam/pixyshapes app. Each controller always sends a pixy/servo_control topic at the fixed unique ownership strength relative to it’s voted role.

Upon switchover, the ‘matching’ pixy/servo_control commands may differ by an acceptable error factor (see Value accuracy match above). Thus, the pixy servo may have a slight jitter movement between switchovers and then track per normal operation.

DDS Mechanisms Discussed:

DDS Mechanism	Component Used*	Description
Liveliness	Controller Components	Detects a redundant component / participant failure
Ownership	Between Controller and Actuator	Enables the receiving application, independent of the redundancy strategy used to see at most two samples (one on each bus A and B)
Key’d data	Controller Components	Enables redundant components to use liveliness to detect each controller in a 3-way voting system
Match on Publisher	Controller Components	Enables the system to determine how many controllers are active.
Durability**	Controller Components	Allows a so called “Late Joiner” to be a part of a running system. This may include obtaining system state or a number of previous samples to integrate to quickly get within the acceptable error value to become a Hot Standby.
Explicit Application Level Acknowledgement	Controller Components	Discussed above, but not suitable for this application.

* Shown only for a simple example where Controller only publishes and Actuator only subscribes. In a closed loop system add the Actuator Component or ‘Between Actuator and Controller’

** Durability is not used in the FAE project implementation, but where data is integrated to get result, a newly joined controller would require a grace period of n-samples to get enough integration to be ‘in spec’. Using durability could shorten this grace period (i.e. amount of time to be fully redundant)

Interesting Observations

DDS Ownership decouples Switchover Time from the (re)voting process.

Using DDS Ownership, QoS decouples the "Switchover Time" from the time to revote and elect a new Primary. When the Primary fails, after the Pixy/Servo topic deadline is missed, the Secondary's sample will be sent to the application. Voting can then go on in the background to promote the Secondary (and associated writer strength) to the Primary.

Exclusive Ownership on aperiodic topics -

Topics that are not periodic and have Exclusive Ownership, such as the pixy/Servo topic, behave interestingly. Exclusive Ownership uses a deadline expiration for DDS to send the next highest strength writer's sample to the application. Aperiodic topics may routinely miss deadlines and could cause DDS to act on a sample from a lower-strength writer. After the deadline is missed, if all writers of the topic send samples in unison and the lower strength sample arrives first, that sample will be passed up to the application. Because the higher-strength writer is also writing, once the higher-strength sample is received, DDS will send only higher-strength samples until the deadline is again missed. There are three solutions to this issue: 1) Do nothing. This is applicable IFF an extra sample with similar or the same data will not cause a problem. 2) Make the topic periodic. If data is not changing, send the last sample before the deadline expires. 3) Don't use Excessive Ownership. Instead, allow only the Primary writer to send samples (i.e., one writer at a time. This impacts switchover time as it is now dependent upon the time necessary to recognize a missing heartbeat (or two), revote, evaluate the results, and enable the new Primary Controller.

Dev Plan:

Development can be done on a host PC will three different Tracker apps running, prior to being moved the each Raspberry Pi

1. +Put 64-Bit Debian Linux (Bullseye) on RPI 4
2. +Put 64-Bit Debian Linux (Bullseye) and DDS 7.2. on RPI3s - 3 of them
3. +Recompile PixyShapes (With Pixy Cam) on RPI 4 with DDS 7.2
4. +Add ownership to servo-control topic - show it works
5. +Get GPIO package running on RPI3s to provide LED status
6. +Convert PIxyTracker to C++11 using multitopic code factoring wrappers (on mac)
7. + Add in Heartbeat and voting topics
8. + Add Voting algorithm and change ownership on servo-control topic accordingly
9. + Add LED update main thread
10. + Move to RPI3s
11. O Test the ever living $h|T out of it to ensure it correctly operates in all scenarios