

Article

ROSMOD: A Toolsuite for Modeling, Generating, Deploying, and Managing Distributed Real-time Component-based Software using ROS[§]

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Abstract: This paper presents ROSMOD, a model-driven component-based development tool suite for the Robot Operating System (ROS) middleware. ROSMOD is well suited for the design, development and deployment of large-scale distributed applications on embedded devices. We present the various features of ROSMOD including the modeling language, the graphical user interface, code generators, and deployment infrastructure. We demonstrate the utility of this tool with a real-world case study: an Autonomous Ground Support Equipment (AGSE) robot that was designed and prototyped using ROSMOD for the NASA Student Launch competition, 2014–2015.

Keywords: robotics; distributed; real-time; embedded; cyber-physical; timing; analysis; model-driven; development.

1. Introduction

Distributed Cyber-Physical Systems (CPS) are hard to develop hardware/software for; because the software is coupled with the hardware and the physical system, software testing and deployment may be difficult - a problem only exacerbated by distributing the system. All systems require rigorous testing before final deployment, but may not be able to be tested easily in the lab or may not be testable in the real world without first providing the assurances that testing produces, especially with respect to reliability and fail-safety. Examples of these systems include unmanned aerial vehicle (UAV)/unmanned underwater vehicle (UUV) systems, fractionated satellite clusters [1], and networks of autonomous vehicles, all of which require strict guarantees about not only the performance of the system, but also the reliability of the system.

Developing systems in a design-test-integrate-iterate methodology is standard practice especially for hardware systems, where electrical and mechanical components can be prototyped and unit-tested before performing higher-level system integration testing. This development approach becomes more challenging when developing software however, since there do not exist well-adopted pervasive standard interfaces and design principles for software.

25 Emerging industry standards and collaborations are progressing towards component-based
26 system development and reuse, e.g. AUTOSAR[2] in the automotive industry. As these systems
27 are becoming increasingly more reliant on collections of software and hardware components which
28 must interact, they enable more advanced features, and performance, but must still meet stringent
29 safety requirements and as a consequence require more thorough integration testing. Comprehensive
30 full systems integration is required for system analysis and deployment, and the development
31 of relevant testing system architectures enables expedited iterative integration. Developing these
32 systems manually, by prototyping individual components and composing them can be expensive,
33 time consuming and error prone, so tools and techniques are needed to expedite this process.

34 Examples of such systems which can be prototyped and tested using this architecture are (1)
35 autonomous cars, (2) controllers for continuous and discrete manufacturing plants, and (3) UAV
36 swarms. Each of these systems is characterized as a distributed CPS in which embedded controllers
37 are networked to collectively control a system through cooperation. Each subsystem or embedded
38 computer senses and controls a specific aspect of the overall system and cooperates to achieve the
39 overall system goal. For instance, the autonomous car's subsystems of global navigation, pedestrian
40 detection, lane detection, engine control, brake control, and steering control all must communicate
41 and cooperate together to achieve full car autonomy. The control algorithms for each of these
42 subsystems must be tested with their sensors and actuators but also must be tested together with
43 the rest of the overall system. It is these types of cooperating embedded controllers which are a
44 distinguishing feature of distributed CPS.

45 In the field of Robotics, adoption of Robot Operating System (ROS) [3] has become widely
46 prominent. ROS is a meta-operating system framework that facilitates robotic system development.
47 ROS is widely used in various fields of robotics including industrial robotics, UAV swarms and
48 low-power image processing devices. The open source multi-platform support of ROS has made
49 it a requirement in several DARPA robotics projects including the *DARPA Robotics Challenge* [4].

50 This paper describes ROSMOD [5], an open source development tool suite and run-time
51 software platform for rapid prototyping of component-based software applications using ROS. Using
52 ROSMOD, an application developer can create, deploy and manage ROS applications for distributed
53 real-time embedded systems. We define a strict component model, and present a model-driven
54 development workflow with run-time management tools to build and deploy component-based
55 software with ROS. The utility of ROSMOD is demonstrated using a real-world case study:
56 an Autonomous Ground Support Equipment (AGSE) robot that was designed, prototyped and
57 deployed for the NASA Student Launch Competition [6] 2014-2015. We describe the challenges and
58 requirements, the robotic design, the software prototyping and the overall performance that led us to
59 winning this competition.

60 1.1. ROSMOD Component Model

61 Software development using ROSMOD is influenced by the principles of Model Integrated
62 Computing[7] and Component-based Software Engineering [8][9]. Large and complex systems can
63 be built by assembling reusable software pieces called *components*. These components are specified
64 by well defined execution semantics and interaction patterns. With this model of a component's
65 behavior, more complex software can be created as the composition of multiple components and
66 a mapping between the input/output ports of the components. ROSMOD components contain
67 executable code that implement functions, manipulate state variables and interact with other
68 components in applications. This model is inspired by our previous efforts with the F6COM
69 Component Model [10].

70 Here, ROSMOD is focused on improving the software development workflow for ROS
71 applications. ROS provides a light-weight middleware framework for a variety of interactions
72 between processes via a communications broker. However, the development of ROS applications
73 is neither model-driven nor component-based; ROS processes, called *nodes*, are assembled together

74 into a *package* and interact using the supported set of ROS *ports*. ROS defines certain types
 75 of input and output ports that are available with either blocking or non-blocking semantics:
 76 *publish-subscribe* interactions enable non-blocking one-to-many one-way transport of data while
 77 *client-server* interactions enable blocking send/receive one-to-one interactions. In these interactions,
 78 the publishers and clients act as the output ports and therefore trigger subscriber and server input
 79 ports. In these interactions, input ports trigger *operations* which can execute arbitrary code. Such
 80 nodes can also be triggered by timers for time-triggered operations e.g. periodic camera feeds.
 81 It is important to note that ROS imposes no design constraints or principles on the nodes; they
 82 can be any process with any number of threads, shared memory, etc. The goals of ROSMOD are
 83 to provide a component model with clear execution semantics coupled with design principles for
 84 multi-threaded distributed code, and a model-driven development tool suite for rapid prototyping of
 85 ROS applications, while receiving the numerous benefits of component-based software engineering.

86 ROSMOD components, as shown in Figure 1, can contain a variety of ports and timers. Publisher
 87 ports publish messages, without blocking, on a message topic. Subscriber ports subscribe to such
 88 topics and receive all messages published on the specified topic. This interaction implements an
 89 anonymous topic-driven publish-subscribe message passing scheme [11]. Server ports provide
 90 an interface to a component service. Client ports can use this interface to request such services.
 91 Clients and servers implement a blocking peer-to-peer synchronous remote method invocation (RMI)
 92 interaction [12]. Component timers can be periodic or sporadic and allow components to trigger
 93 themselves with the specified timing characteristics. ROSMOD components, upon deployment, are
 94 dormant. Execution of the application is first initiated by a timer-triggered component. The executor
 95 thread of the triggered component wakes up and executes the *trigger operation*. The application code
 96 written in this operation may initiate other triggers and component interactions, thus dictating the
 97 behavior of the ROSMOD application.

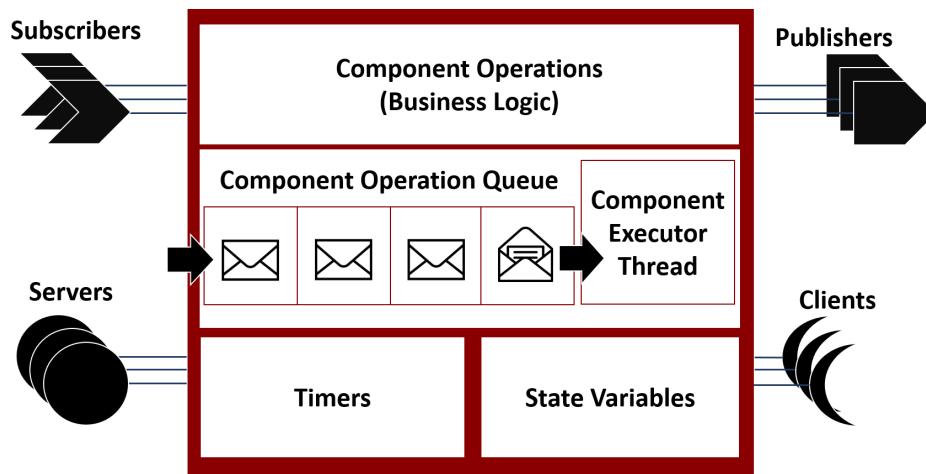


Figure 1. ROSMOD Component

98 Here, an *operation* is an abstraction for the different tasks undertaken by a component. These
 99 tasks are implemented by the component's executor code, written by the developer. Application
 100 developers provide the functional, *business-logic* code that implements operations on the state
 101 variables. In order to service interactions with the underlying framework and with other components,
 102 every component is associated with a *operation queue*. This queue holds instances of operations
 103 that are ready for execution and need to be serviced by the component. These operations service
 104 either interaction requests (as seen on communication ports) or library-specific requests (from the
 105 underlying framework). In each ROSMOD component, the operation queue is processed by a
 106 single executor thread. Multiple components may run concurrently but each component's execution
 107 is single-threaded. Also, the component operation queue supports several scheduling schemes

108 including FIFO (first-in first-out), PFIFO (priority first-in first-out) [13] and EDF (earliest deadline
 109 first) [14]. Operations in the operation queue are executed using a non-preemptive scheduling
 110 scheme. This scheduling scheme means that each operation run by the executor thread is run to
 111 completion before the next operation in the queue is processed. The use of this component execution
 112 model is to enable composable, single-threaded components which can communicate with each other
 113 through the underlying ROS middleware without the developer having to deal with locking shared
 114 resources or dealing with other related multi-programming issues that typically introduce difficult
 115 to debug errors or other run-time issues. Again, following component-based software design allows
 116 these components to encapsulate related functionality into a reusable piece of software that can be
 117 shared between projects and systems that require that functionality.

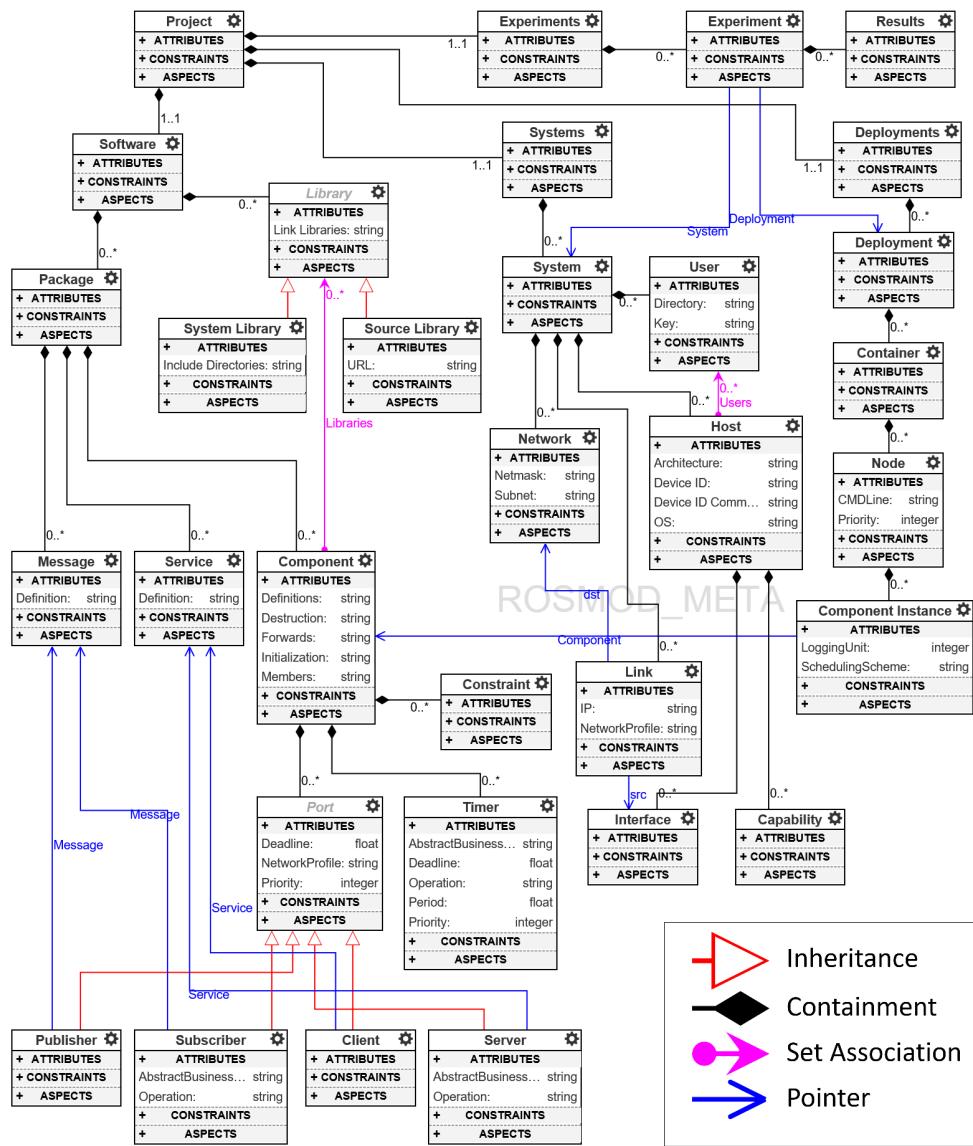


Figure 2. ROSMOD Metamodel. Containment is specified from *src* to *dst* where the source has a containment attribute *quantity*, meaning that *quantity* objects of type *src* can be contained in an object of type *dst*. Pointers are specified as a one to one mapping from source to destination, using the name of the pointer. Sets allow for pointer containment. All objects contain a *name* attribute of type *string*, not shown for clarity. Note: the meta-model is used to create the ROSMOD Modeling Language, but users do not see or interact with it; it is used to enforce proper model creation semantics.

118 1.2. ROSMOD Modeling Language

119 To enable the design, development, and testing of software on distributed CPS, we have
 120 developed a modeling language specific to the domain of distributed CPS which utilize ROS, the
 121 ROSMOD Modeling Language (RML), shown in Figure 2. RML captures all the relevant aspects
 122 of the software, the system (hardware and network), and the deployment which specifies how the
 123 software will be executed on the selected system. Using ROSMOD, developers can create models
 124 which contain instances of the objects defined in RML. This approach of using a domain specific
 125 modeling language to define the semantics of the models allows us to check and enforce the models
 126 for correctness. Furthermore, this approach allows us to develop generic utilities, called *plugins* which
 127 can act on any models created using ROSMOD, for instance generating and compiling the software
 128 automatically or automatically deploying and managing the software on the defined system. The rest
 129 of this section goes into the specific parts of the modeling language, called the Meta-Model, and how
 130 they define the entities in a ROSMOD Model.

131 The top-level entity of RML is a *Project*, which is shown in the upper left of Figure 2. The
 132 language supports a variety of modeling concepts that address structural and behavioral aspects
 133 for distributed embedded platforms. ROSMOD users can create models of software workspaces,
 134 required software libraries, embedded devices, network topologies, component constraints and
 135 hardware capabilities. The language also supports code development, particularly with regards
 136 to port interface implementations i.e. the execution code for operations owned and triggered
 137 by communication ports or local timers. Below, we describe in detail the various aspects of
 138 this meta-model and how these concepts are integral to developing distributed CPS and rapid
 139 prototyping needs.

140 1.2.1. Software Model

141 The *Software* class in Figure 2 models a software workspace. A workspace, following ROS
 142 terminology, is a collection of applications that are developed and compiled together into binaries.
 143 Thus, each Software class can contain ROS applications, called *Packages*, and *Libraries* required for
 144 the applications. Packages consist of *Messages*, *Services* and *Components*. Components contain a set
 145 of pointers to Libraries to establish dependence e.g. an *ImageProcessor* component *requires* OpenCV,
 146 an open-source computer vision library. Libraries are of two types: Source libraries and System
 147 libraries. Source libraries are standalone archives that can be retrieved, extracted and integrated into
 148 the software build system with no additional changes. System libraries are assumptions made by
 149 a software developer regarding the libraries pre-installed in the system. Here, system refers to the
 150 embedded device on which the component is intended to execute.

151 *Messages* represent the ROS message description language for describing the data values
 152 used by the ROS publish-subscribe interactions. Similarly, *Services* describe the ROS peer-to-peer
 153 request-reply interaction pattern. Each service is characterized by a pair of messages, *request* and
 154 *response*. A client entity can call a service by sending a request message and awaiting a response.
 155 This interaction is presented to the user as a remote procedure call. Each ROSMOD component, as
 156 described in the component model (Figure 1), contains a finite set of communication ports. These
 157 ports refer to messages and services to concretize the communication interface. Components can also
 158 contain *Timers* for time-triggered operation e.g. periodically sampling inertial measurement sensors
 159 while operating an unmanned aerial vehicle (UAV). Lastly, components can be characterized by
 160 *Constraints*. Currently, ROSMOD constraints are a simple way to establish hardware requirements
 161 for operation e.g. fast multi-core processor, quadrature encoded pulse hardware, camera interface
 162 etc. When starting such components at runtime, ROSMOD will try to map each component to one
 163 of the available devices that satisfies all of the component's constraints. Specifying constraints for a
 164 component can be arbitrarily complex but currently we support simple feature-specific constraints
 165 e.g. *This component needs a device with atleast 12 open GPIO pins to enable motor control*. In such cases,
 166 ROSMOD will simply scan the set of devices in the hardware model and find a candidate host that

provides such a *capability*. More about the deployment infrastructure and the mapping of constraints to capabilities is described in Section 1.4.

All requests received by a component, via subscribers or servers, and all timed triggers can be prioritized. The prioritization is used primarily by the component scheduler and the chosen scheduling scheme. First-in-first-out (FIFO) scheduling of received operations prioritizes based on the arrival time of the requests. Priority-based FIFO resolves conflicts between received operations by using the *Priority* attribute of the relevant ports. Similarly, deadline-based schemes like the Earliest-Deadline-First (EDF) scheme uses the *deadline* of the received operation requests to resolve conflicts and operate safely. The scheduling scheme and operation priorities within a component are important choices to make since these choices directly affect the efficiency and safe operation of components. Highly critical operations need acceptable response times for robotic systems to meet quality and timing specifications. This design criteria is our primary motivation for integrating timing and performance characterization techniques into our software specification and tool suite. The integrated performance and timing measurement system allows for the logging and visualization of system execution traces and to show the enqueue, dequeue, and completion of operations being executed by the component executor thread. As these operations trigger each other, these traces provide valuable feedback to the users about the performance and timing characteristics of the system, allowing the determination of performance bottlenecks and resource contention.

1.2.2. System Model

A *System Model* completely describes the hardware architecture of a system onto which the software can be deployed. A ROSMOD Project contains one or more *Systems*. Each System contains one or more *Hosts*, one or more *Users*, one or more *Networks*, and one or more *Links*. A host can contain one or more *Network Interfaces*, which connect through a link to a network. On this link the host's interface is assigned an IP, which matches the subnet and netmask specification of the network. Additionally, a host has a set of references to users, which define the user-name, home directory, and ssh-key location for that user. The host itself has attributes which determine what kind of processor architecture it has, e.g. *armv7l*, what operating system it is running, and lastly a combination of Device ID and Device ID Command which provide an additional means for specifying the type of host (and a way to determine it), for instance specifying the difference between a BeagleBone Black and an NVIDIA Jetson TK1 which both have *armv7l* architecture but can be separated by looking at the model name in the device tree. Finally, a host may contain zero or more *Capabilities* to which the component constraints (described in the previous section) are mapped. The final relevant attribute is the *Network Profile* attribute of a link. Using the network profile, which is specified as a time-series of bandwidth and latency values, we can configure the links of the network using the Linux TC to enforce time-varying bandwidth and latency. This network configuration is useful when running experiments on laboratory hardware for which the network is not representative of the deployed system's network.

1.2.3. Deployment and Experimentation

Deployment refers to the act of starting application processes on candidate hosts, where each host can provide for and satisfy all of the constraints of the processes e.g. general purpose input/output (GPIO) ports, CPU speed etc. Therefore, a deployment is a mapping between application processes and system hosts on which the application processes run. The ROSMOD Deployment Model makes this map a loose coupling to enable rapid testing and experimentation. Each Deployment consists of a set of *Containers*. Each container, conceptually, is a set of processes that need to be collocated. Containers also ensure that no process outside a container is deployed along with the container once it has been mapped to a host. Each container, therefore, contains a set of *Nodes* (ROS terminology for processes). In each node, application developers instantiate one or more components previously defined in the Software model. Following the ROSMOD component model, each such instance maps

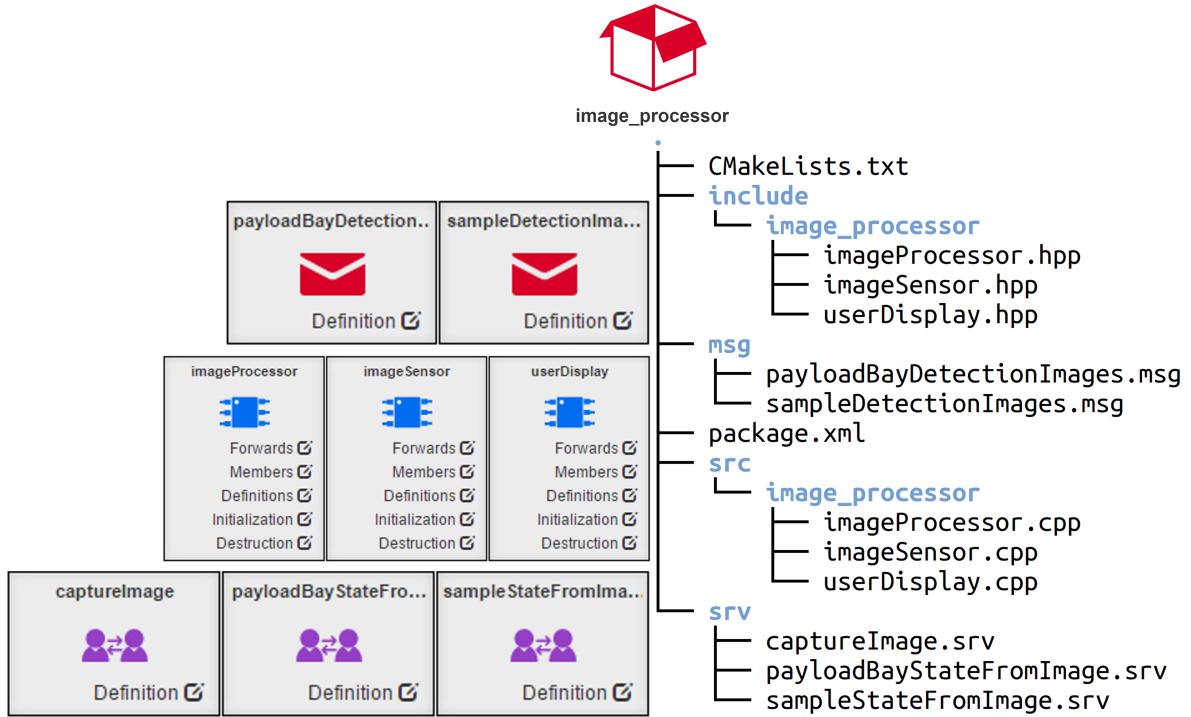


Figure 3. Workspace Code Generation. In this figure, the *image_processor* package and its children messages (red), components (blue), and services (purple) are generated into a catkin package for compilation. The msg and srv files are automatically filled out from the definitions of the messages and services, as are the header and source files for the components.

215 to an executor thread that executes the operations in the component's operation queue. Note that
 216 the same component can be instantiated multiple times even within the same node. Also note the
 217 container is not mapped to a specific host within the deployment model, but rather is automatically
 218 mapped to a host by the deployment infrastructure within an *Experiment*.

219 As shown in Figure 2, each project supports a set of *Experiments*. Each experiment has pointers
 220 to one System model and one Deployment model. The system model provides the set of available
 221 devices and the deployment model provides the set of containers, where each container contains a
 222 set of component constraints that need satisfying (the union of all the container's nodes' component
 223 constraints). ROSMOD uses these sets to find a suitable mapping and then deploys the containers
 224 on the chosen host devices, if a mapping can be found which satisfies all the constraints of all the
 225 containers. When the deployment infrastructure selects hosts from the system model for mapping, it
 226 first checks to see which of the system model's hosts are 1) reachable, 2) have valid login credentials,
 227 3) have the correct architecture, operating system, and device ID, and 3) are not currently running any
 228 other compilation or experiment processes from any other user. In the case that there are no available
 229 hosts in the system or the deployment's constraints cannot be satisfied, the infrastructure informs
 230 the user. Upon successful deployment of the experiment, the infrastructure automatically stores the
 231 specific mapping relevant to the deployed experiment for later management and destruction. When
 232 such experiments are stopped, ROSMOD retrieves the component logs from the hosts and displays
 233 results. We are currently working on improving our runtime monitoring features to enable real-time
 234 component execution plots and network performance measurements at runtime.

235 Such a loose coupling between the deployment model and the system model, along with the
 236 infrastructure automatically mapping the containers to valid, unused hosts enables the execution of
 237 the same deployment onto subsets of a large system, for instance running many instances of the same
 238 deployment as separate experiments in parallel on a large cluster of embedded devices. Additionally

239 such a loose coupling enables redeployment onto a completely different system by simply changing
240 the experiment's system model reference; the infrastructure will automatically verify that the new
241 system meets the constraints of the deployment and has available hosts.

242 **1.3. Software Infrastructure**

243 The ROSMOD software infrastructure provides the user with the tools to generate source code
244 corresponding to the software model, compile that source code to produce binaries that can run on the
245 hosts defined in the system models, and also generate documentation for the software and associated
246 libraries.

247 **1.3.1. ROSMOD Workspace**

248 The Software generator in ROSMOD is a plugin that produces a complete ROSMOD workspace.
249 The application software, as defined in the model, is a collection of packages, each with messages,
250 services, components and required libraries. When invoking the workspace code generation,
251 ROSMOD first generates the ROSMOD packages including C++ classes for each component,
252 package-specific messages and services, and logging and XML parser-specific files. Then, for each
253 external library, the URL of the library archive is used to fetch the library and inject this code as a
254 package into the generated workspace. Assuming the library is stable and the target devices have
255 the necessary system libraries, this generated code compiles without errors out of the box. The
256 meta-model for the software is fully specified to include attributes for user code, the business logic
257 for the components' operations, additional class members, etc. Because these pieces of user code are
258 all captured within the model, they are placed into the proper sections of the generated code. For
259 this reason, it is not necessary to alter the generated code before compilation into binaries. If the user
260 chooses, the software infrastructure for ROSMOD will automatically determine the different types
261 of hosts in all the current project's system models, determine which of those hosts are available that
262 match the model specifications and will compile the source code into binaries for those architectures.
263 The compilation is performed as a remote procedure on the host; therefore the compilation will not
264 select hosts which are currently running other compilation or deployment processes. To enable the
265 user to multi-task, compilation is an asynchronous non-blocking process allowing further interaction
266 with the model or other plugins.

267 Figure 3 shows the generated code tree for an *image_processor* package. This package has three
268 components - *userDisplay*, *imageProcessor*, *imageSensor*, and associated messages and services. For
269 each component, ROSMOD generates a unique class that inherits from a base *Component* class and
270 contains member objects for every component port and timer. Unlike earlier versions of ROSMOD,
271 this generated code is not a skeleton. Rather, it includes all of the operation execution code embedded
272 in the model. So, all changes to this business logic code are done from the model, instead of modifying
273 a skeleton. This ensures code consistency and avoids synchronization issues between the model and
274 the generated code. Furthermore, this enables faster training and use of the ROSMOD tool suite, since
275 users no longer need to know into what folders and files the generated code goes. In the competition
276 version of ROSMOD, a user would have to generate the skeleton code for the workspace, open up the
277 relevant files manually, find the specific places into which to place the business logic for the operations
278 and added members, add extra library code into the generated build files manually, and then inform
279 the infrastructure that the code was ready for compilation. This process was error prone and required
280 detailed knowledge of what files are generated, how to integrate libraries into the build system, and
281 other details that were specific to both ROS' package system and our component implementation.
282 In the current version of ROSMOD, the user is given direct access to only the code relevant for the
283 specific object (component, message, service) they are editing. Furthermore, the library system now
284 enables the creation and use of libraries without knowledge of how the underlying ROSMOD build
285 system works.

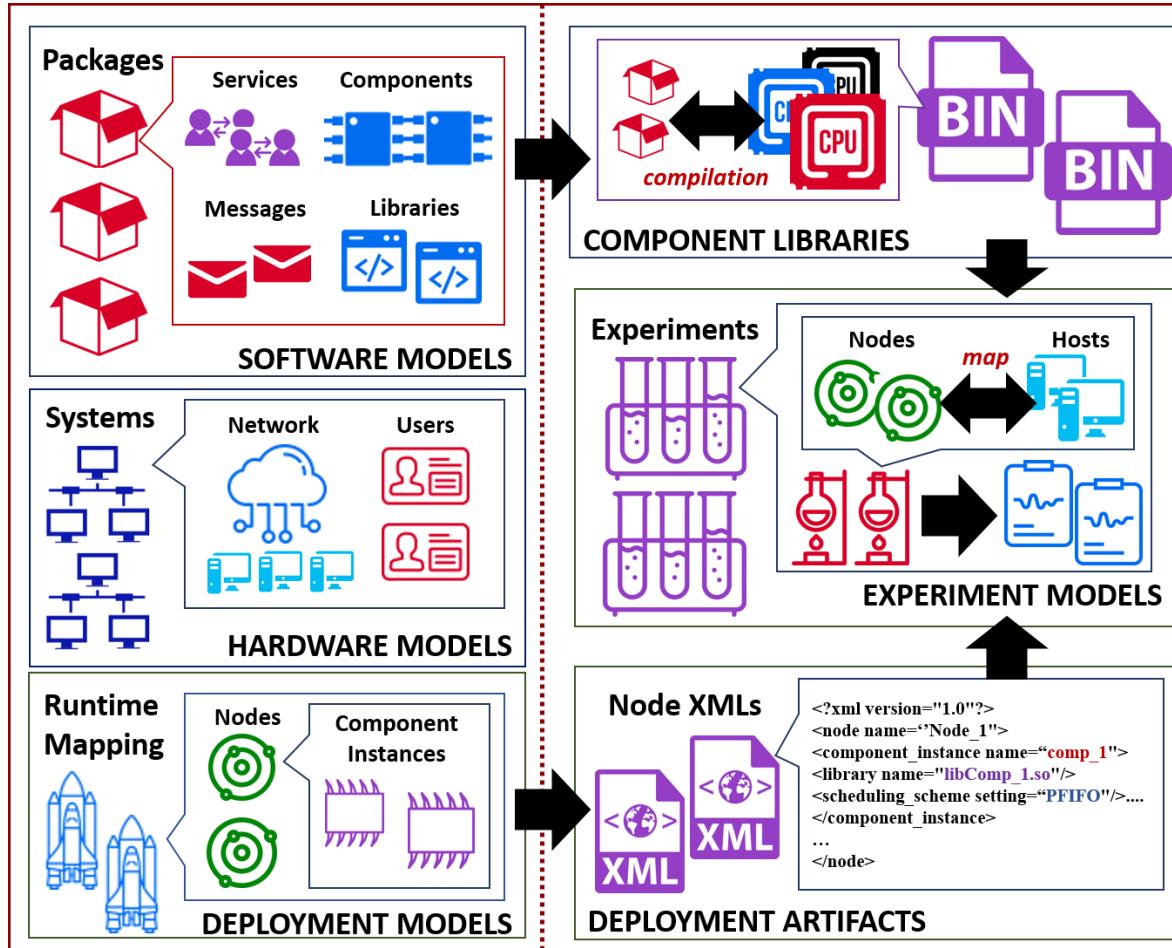


Figure 4. Software Deployment Workflow

286 1.3.2. Class Documentation

287 Along with the source code, ROSMOD also supports generation of Doxygen-style
 288 documentation for all classes and files used in the software model, including external libraries. All
 289 component files, and library directories are scanned and the class hierarchy is constructed from which
 290 documentation, both *html* and *latex*, is automatically generated. The generation of documentation
 291 allows for better project maintenance, description, and training when multiple people are working
 292 on the same project.

293 1.4. Deployment Infrastructure

294 The workflow for software deployment is as shown Figure 4. After the user has generated
 295 and compiled the software model into binary executables, they can run an experiment that has
 296 valid deployment model and system model references. Every ROSMOD workspace is generated
 297 with an additional *node* package. This builds a generic node executable that can dynamically load
 298 libraries. When the software infrastructure generates and compiles the source code for the software
 299 model, the components are compiled into dynamically loadable libraries, one for each component
 300 definition along with a single executable corresponding to the generic node package. The first step the
 301 deployment infrastructure performs when running an experiment is generating the XML files which
 302 contain metadata about each ROS node modeled in the ROSMOD Deployment Model. This metadata
 303 includes the component instances in each node and the appropriate component libraries to be loaded.
 304 Based on the XML file supplied to the node executable, the node will behave as one of the ROS nodes

305 in the deployment model. This allows for a reusable framework where a generic executable (1) loads
306 an XML file, (2) identifies the component instances in the node, (3) finds the necessary component
307 libraries to load and (4) spawns the executor threads bound to each component.

308 The reason for having the components be libraries that are loaded at run-time by a node
309 executable is 1) to help enforce separation between each component's code, 2) to shorten the
310 compilation time (which may be quite long for embedded processors and complex models), and
311 most importantly 3) to enable the ability for users to change the mapping of component instances
312 to processes without the need to recompile any of the code. Because ROSMOD is focused on the
313 rapid development and deployment of reusable software components, we designed the infrastructure
314 to allow users to experiment with which components are collocated within processes dynamically
315 and rapidly iterate through several scenarios and experiments without having to wait for code
316 compilations between experiments. Finally, such a component-based deployment framework enables
317 unit testing and integration testing in a very well-defined manner for the software components. If
318 an error occurs during the execution of an application on a system, the user can easily and quickly
319 break the deployment down into sub-deployments for unit-testing of only the relevant components
320 to determine the source of the error.

321 In the above architecture, the deployment needs three primary ingredients: (1) the generic node
322 executable, (2) dynamically loadable component libraries, and (3) an XML file for each ROS node in
323 the deployment model. For each new node added to the deployment model, by merely regenerating
324 the XML files, we can establish a new deployment. The ROS workspace is rebuilt only if new
325 component definitions are added to the Software Model. This architecture not only accelerates the
326 development process but also ensures a separation between the Software Model (i.e. the application
327 structure) and deployment-specific concerns e.g. component instantiation inside ROS nodes.

328 When the user has selected an experiment to run, the deployment infrastructure first determines
329 whether the selected deployment can execute on the selected system. Like the software infrastructure
330 described above, the deployment infrastructure queries the selected system to validate that the system
331 is reachable, conforms to the model, and has available hosts for deployment (i.e. they are not
332 currently running any compilation or deployment processes). Once those available hosts have been
333 determined, the infrastructure attempts to map the deployment's containers to the available hosts
334 based on the constraints and capabilities of the two sets. If the constraints cannot be satisfied by
335 the capabilities of the available hosts, the user is informed and the deployment of the experiment is
336 halted. If the capabilities of the hosts do satisfy the constraints of the containers and their associated
337 components, the deployment infrastructure generates the required XML files for the deployment and
338 copies the XML files and the binaries over to the selected hosts, before starting the relevant processes.
339 Finally, if all of those steps are successful, the infrastructure saves the mapping into the model for
340 user inspection and for later teardown of the experiment.

341 When the user chooses to end a currently running experiment, the deployment infrastructure
342 verifies that the experiment is still running before stopping the associated processes, copying the
343 relevant log files back, cleaning up the deployment artifacts from the hosts, and removing the saved
344 experiment mapping from the model.

345 2. Experimental Section

346 2.1. Case Study: Autonomous Ground Support Equipment (AGSE) Robot

347 This section briefly describes an Autonomous Ground Support Equipment (AGSE) robot that
348 we designed, built, and deployed for the 2014-2015 NASA Student Launch Competition [6]. Special
349 emphasis is given to the value of a rapid system prototyping methodology in the design process and
350 how it allowed the AGSE to overcome many of the challenges and problems encountered during
351 the competition. We use this example to demonstrate the utility of our integrated model-driven
352 component-based software tool suite.

353 2.2. Competition Requirements

354 The NASA Student Launch Initiative [6] is a research-based competition partnered with NASA's
355 Centennial Challenges, and aims to stimulate rapid, low-cost development of rocket propulsion
356 and space exploration systems. Both collegiate and non-academic teams participate in the 8-month
357 competition cycle composed of design, fabrication, and testing of flight vehicles, payloads, and
358 ground support equipment.

359 The purpose of the 2014-2015 competition was to simulate a Mars Ascent Vehicle (MAV) and to
360 perform a sample recovery from the Martian surface. The requirements for this simulation were
361 twofold: (1) Design and deploy a system termed the Autonomous Ground Support Equipment
362 (AGSE) that independently retrieves a sample off the ground and stores it in the payload bay of a
363 rocket, and (2) launch the rocket to an altitude of 3000 ft. before safely recovering the sample.

364 2.3. AGSE Project Architecture

365 The sample retrieval was accomplished using a robotic arm with computer vision to find the
366 sample and identify its orientation. After successfully acquiring the sample, the system will then
367 search for the payload bay, identify its orientation, and place the sample within it. The robot arm
368 itself is a simple crane-style device akin to a pick-and-place robot with a four-pronged gripper as
369 the end effector. It was designed to have a cylindrical workspace in order to most efficiently access
370 the ground around the system and rocket. It starts in a known position and incrementally scans its
371 workspace using a built in camera. Image processing is performed to identify key environmental
372 features such as the sample and payload bay. The control flow in the AGSE software is shown in
373 Figure 5.

374 While the driving requirements of the competition were fixed, many of the minor rules regarding
375 AGSE performance, behavior, and safety requirements evolved and were augmented throughout
376 the course of the competition. The volatile nature of these rules combined with the short eight
377 month duration of the build cycle precipitated the need for rapidly adjustable design and fabrication
378 processes. As such, an iterative, modular, design-build-test approach was implemented in order
379 to concurrently develop as many components of the hardware and software systems as possible.
380 An initial AGSE prototype was conceptualized from off-the-shelf components and the mechanical
381 and software systems were built in parallel, integrated, and tested. These preliminary results were
382 then used in future development to produce a more ideal structure with greater positional accuracy
383 and system robustness. Due to the modular nature of the system's design, it was not necessary to
384 immediately build a completely new second system, so incremental improvements could be made
385 on a specific subsystem (such as the robot's gripper, any single degree of freedom, image processing,
386 motor control, etc.) as the design evolved.

387 2.3.1. Distributed Deployment

388 The AGSE robot is controlled by a distributed set of embedded controllers. Figure 6 shows
389 the high-level design for the deployment architecture. There are three embedded devices, each
390 with its own responsibilities. The reasons for the use of multiple embedded controllers cooperating
391 was two-fold: 1) given the design decision to fully automate the robot to search the workspace for
392 both the sample and the payload bay, we needed an embedded processor capable of performing
393 image-based object detection and 2) given the design of the robot to search a workspace with the
394 given degrees of freedom, we needed an embedded processor with the required available General
395 Purpose Input/Output (GPIO) and Special Function Input/Output (SFIO) pins.

396 To meet the first requirement, we selected the NVIDIA Jetson TK1, which is an embedded ARM
397 controller with 4+1 ARM cores and 192 CUDA cores, that consumes 10 W or less. We could not
398 use the Jetson to meet the second requirement since it does not support enough GPIO to control
399 the linear actuators and retrieve feedback from them. Furthermore, it lacks SFIO for encoder pulse

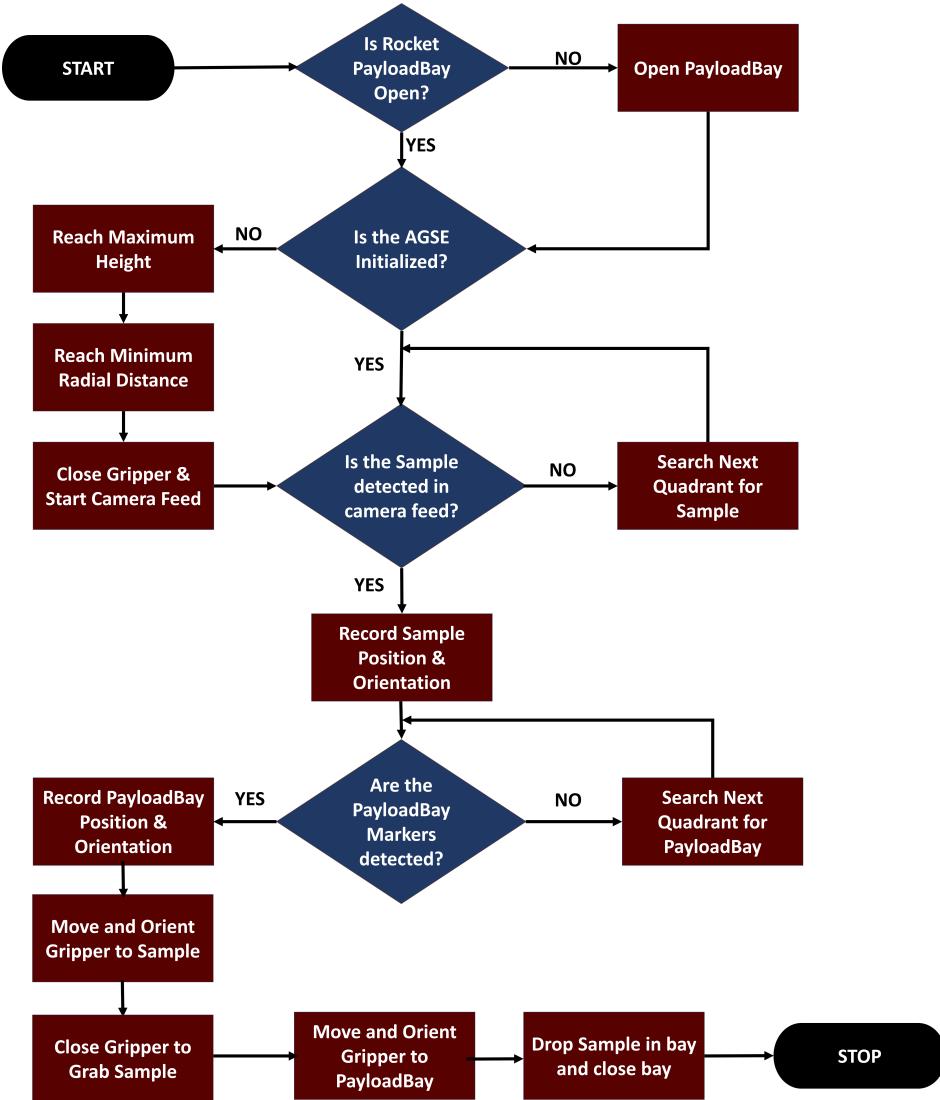


Figure 5. AGSE Control Flow Chart

decoding. Therefore, a BeagleBone Black was selected for the motor control interface board because it has specific hardware for decoding quadrature encoded pulses (QEP) and enough available GPIO for controlling the linear actuators and reading limit switches.

Since one of the secondary requirements of the competition governed pause control and state feedback to the operator of the AGSE (during the competition execution), a second BeagleBone Black was introduced which served to provide mechanical safety switches for pausing the AGSE, LED panels indicating the state of the AGSE, and a touchscreen showing what the AGSE sees as it searches the workspace for the sample and the payload bay. This BeagleBone Black resides the User Interface Panel (UIP).

The NVIDIA Jetson TK1 periodically fetches the latest webcam feed, performs image processing and high-level path planning, and updates a global state machine. The Beaglebone Black (BBB) mounted on top of the robot performs power management, low-level motor control and feedback processing. Lastly, the User Input Panel (UIP) houses a second Beaglebone Black which reacts to user input through switches and provides feedback through touchscreen display and LED panel display. The UIP also responsible for keeping the user informed about the real-time state of the AGSE and the current webcam feed. Each of these controllers host multiple ROS nodes with ROSMOD component

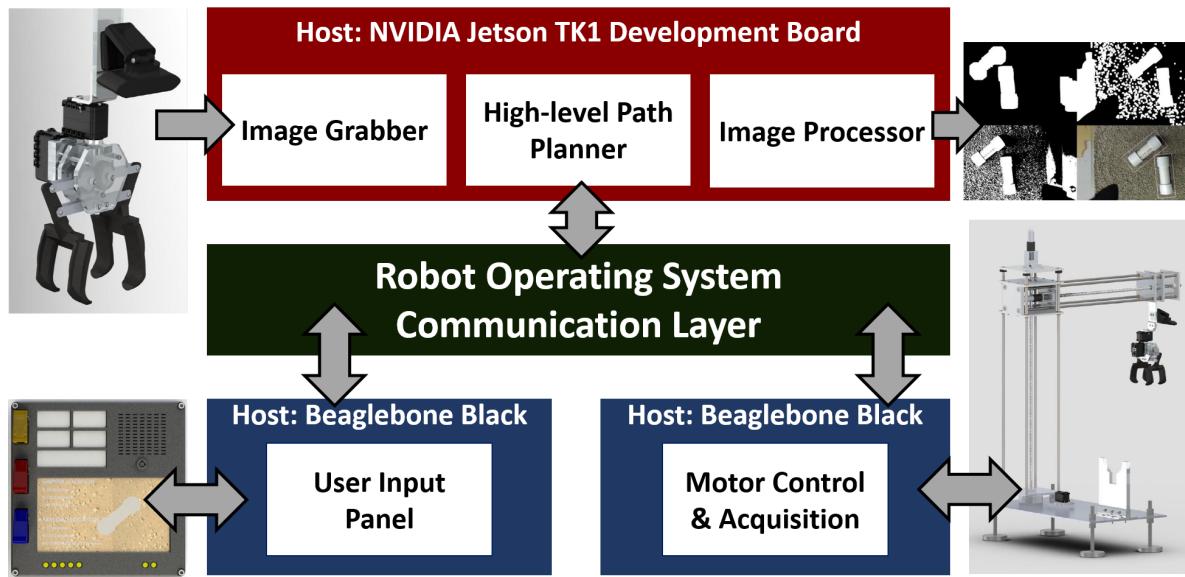


Figure 6. AGSE Package Deployment

416 executor threads periodically performing algorithmic computations, calculating new robotic paths
 417 and communicating to coordinate and maintain the AGSE state.

418 **2.3.2. Software Prototyping with ROSMOD**

419 The AGSE software was iteratively designed and rapid prototyped using our ROSMOD tool
 420 suite. The Software Model consists of 8 components spread across three ROS packages - motor
 421 control, high-level state machine control and image processing. Each package is characterized by
 422 its local set of messages, service and interacting components. Note that just as in ROS, packages
 423 can share messages so that components can subscribe/publish/provide/require messages/services
 424 from other packages. Figure 7 shows the component assembly and wiring as per the design. The
 425 *radialControl* and *verticalControl* components are responsible for radial and vertical actuation of the
 426 AGSE respectively. The *rotationControl* component is capable of controlling three servo motors: (1) the
 427 base rotation servo, (2) the gripper rotation servo, and finally the (3) gripper position servo that opens
 428 and closes the robot gripper. A *Camera* component deployed on the NVIDIA Jetson TK1 provides a
 429 direct interface to the camera. Using the *CaptureImage_Server*, the *ImageProcessor* component receives
 430 a snapshot of the camera feed for periodic processing needs. This feed is also used by the *userDisplay*
 431 component to display the feed on the user input panel, as shown in Figure 6. The user input panel is
 432 the primary interface between the ROSMOD applications and the user. The *userDisplay* component
 433 provides information to the user and the *userInputControl* receives data from the user, specifically to
 434 read the various control switches on the panel e.g. the pause, alarm, and debug switches. Lastly, a
 435 *HighLevelControl* component orchestrates the high-level state transitions and controls the operation
 436 of the robotic arm. These transitions include commands such as *find_payload_bay*, *find_sample*,
 437 *move_to_target* etc., each of which publishes messages to other components to propagate the motor
 438 control commands.

439 The ROSMOD code generators enabled generation of nearly 60% (6,000+ lines) of the total built
 440 code. As mentioned before, much of this code includes port initialization, build system files, callback
 441 skeletons, etc. that usually take up a significant amount of development time. As developers, we had
 442 to fill in the missing pieces - the business logic of the callbacks, completing the component interaction

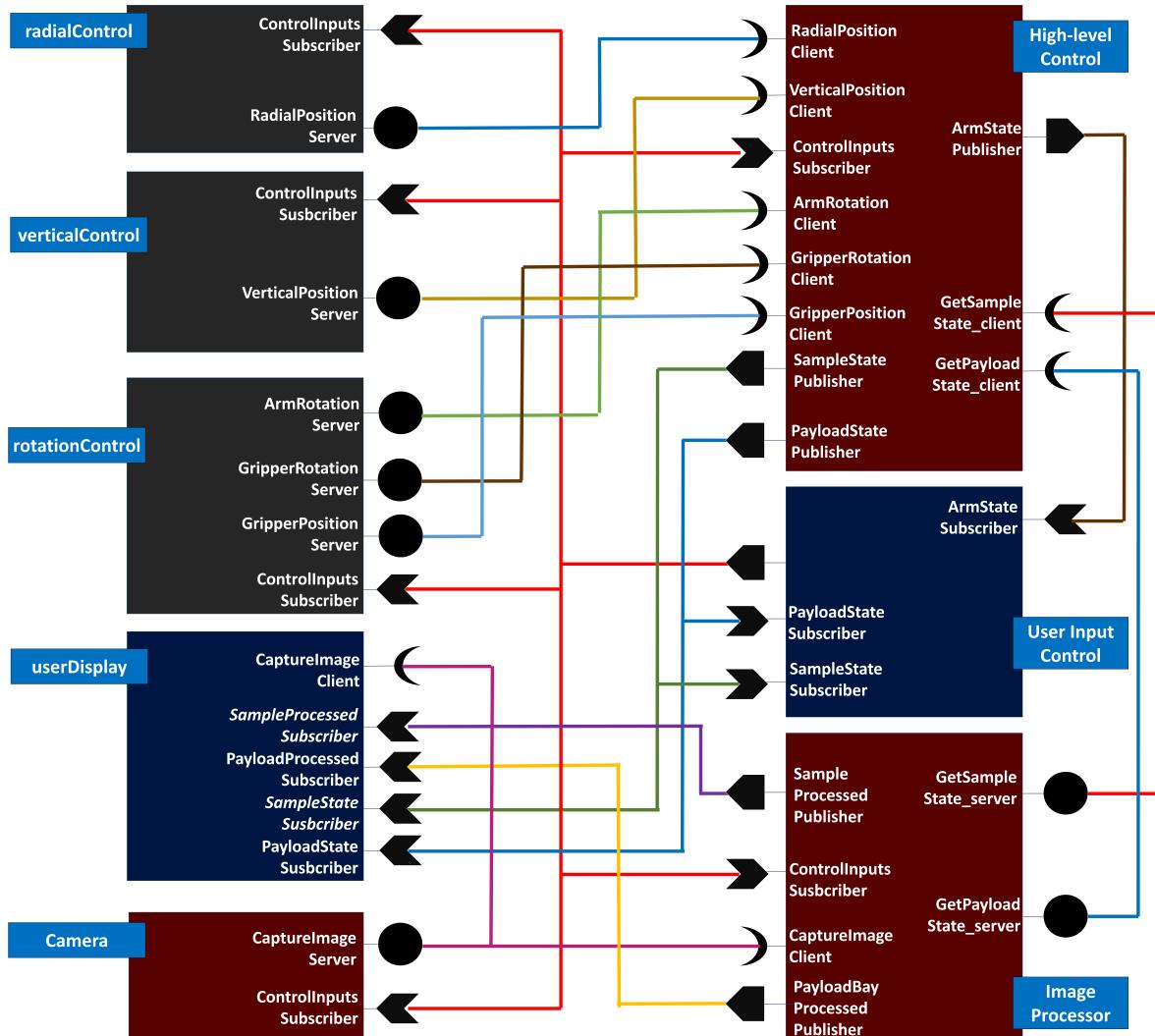


Figure 7. AGSE Component Assembly

443 loops. This code includes architecture-specific control, e.g. GPIO and encoder readings, LED and
 444 switch settings, camera image acquisition, and high-level control.

445 The final AGSE used in the 2014-2015 NASA SLI competition is shown in Figure 8.

446 3. Results

447 3.1. Performance Assessment

448 At the competition, the Vanderbilt AGSE was able to complete the sample retrieval process in
 449 approximately 4.5 minutes. The recovery process, as shown in Figure 9, was successful, with payload
 450 and rocket bay recognition occurring quickly and efficiently. The AGSE was able to grasp the payload
 451 using only two of its four padded end effector phalanges, and successfully deposited the payload
 452 within the rocket bay. This operation received high marks from the NASA officials and earned the
 453 competition's *Autonomous Ground Support Equipment Award*.

454 System robustness was validated on the day of competition when a key component failed and
 455 was able to be quickly replaced with a different part with no detriment to system performance. The
 456 Dynamixel AX-12A servo controlling the base rotational degree of freedom of the AGSE suffered
 457 an irreparable failure of its gearbox and had to be removed from the robot. A backup of the servo

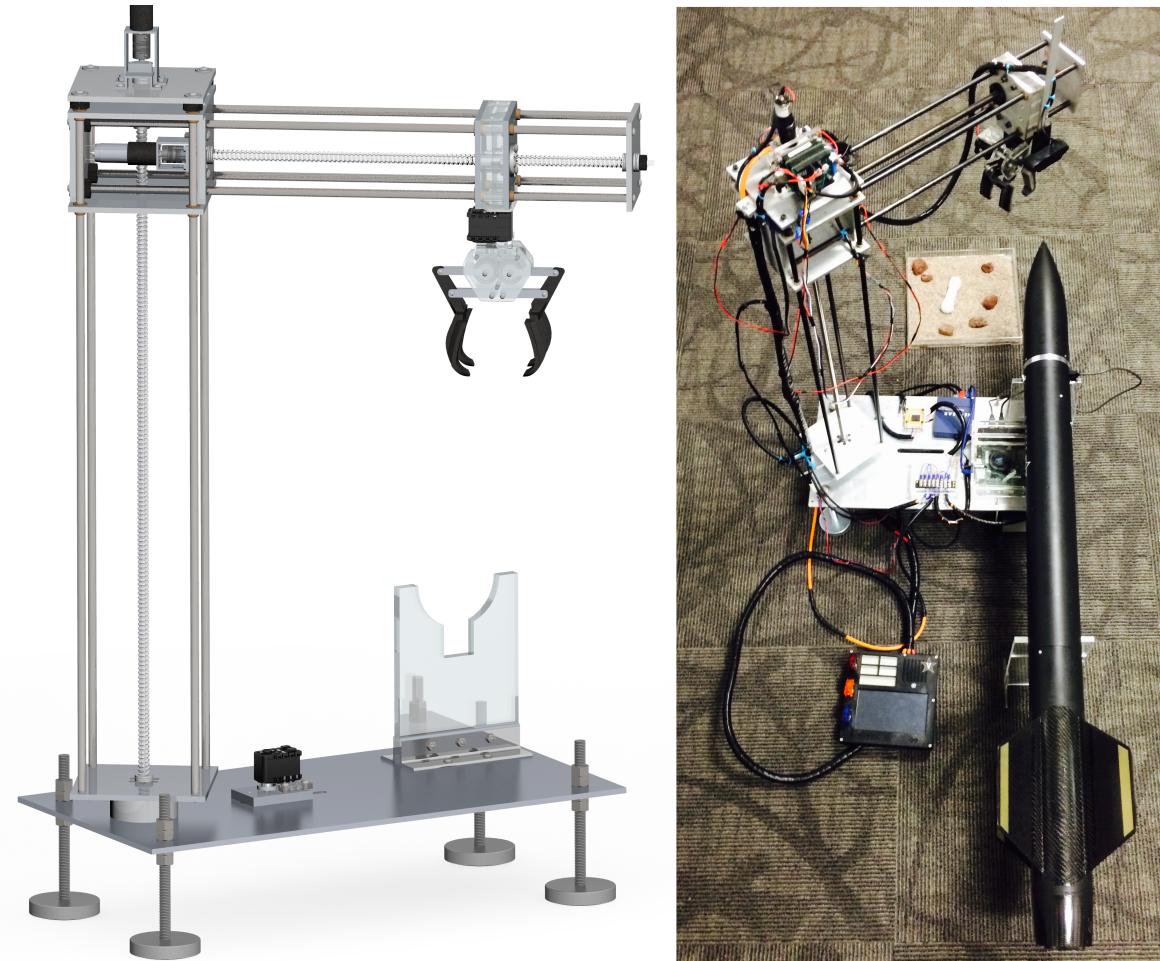


Figure 8. AGSE and rocket used in the 2014-2015 NASA SLI competition. The UIP is shown in the bottom left of the picture, the Motor Control Board is on the top of the arm of the AGSE, and the NVIDIA Jetson is under the rocket.

458 was not readily available, and a different model servo by the same company had to be swapped in
 459 instead. This new model, a Dynamixel MX-28T, while having similar performance as the old servo,
 460 had a different communication protocol and mounting footprint, as well as a more complex control
 461 scheme.

462 The component-based nature of ROSMOD allowed quick modifications of the business logic of
 463 the *rotation_controller* component to update the system to use the new hardware. The new control
 464 scheme was quickly implemented and the control software was updated to account for the new
 465 physical placement of the servo due to its different mounting footprint. After these modifications
 466 were made, the AGSE was able to perform at its optimal level during its part of the competition.

467 4. Discussion

468 The goal of ROSMOD is to be a model-driven, component-based rapid development,
 469 deployment, and experimentation tool suite for distributed CPS. This goal has been the driving
 470 force since the beginning of ROSMOD during the 2014-2015 NASA SLI competition with the AGSE.
 471 ROSMOD itself was developed alongside the AGSE and in concert with it; as we added features
 472 to the modeling language, the user interface, or the generation and deployment infrastructure, we
 473 immediately tested them with the AGSE. The focus on the development was always model-driven
 474 engineering coupled with component-based software design principles enabling an iterative

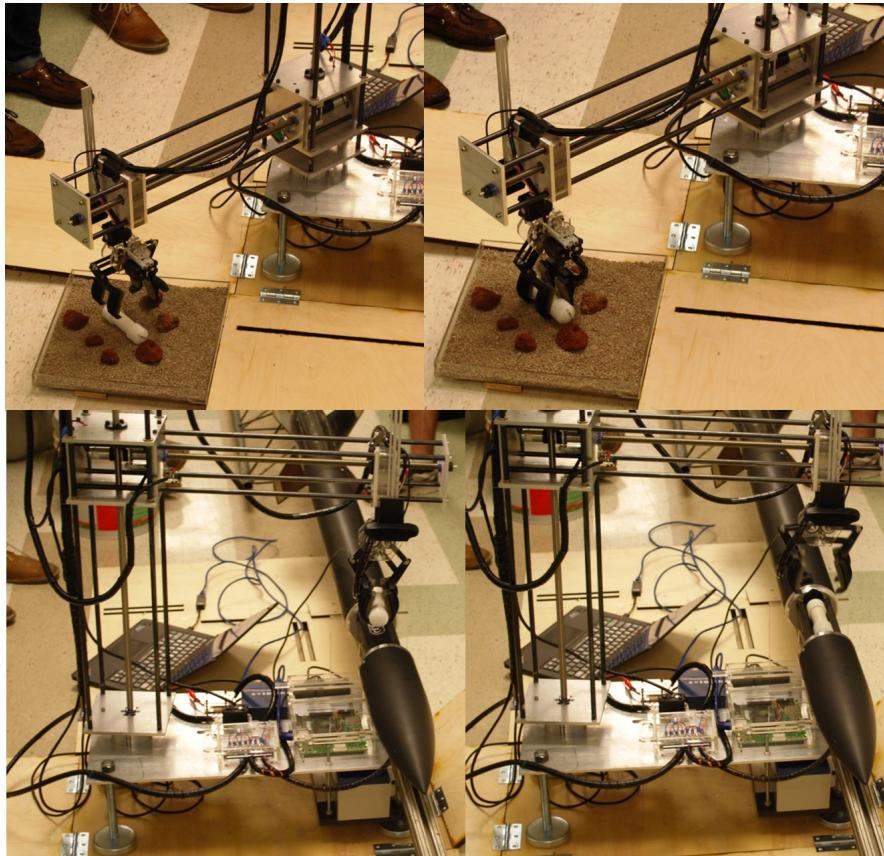


Figure 9. AGSE Calibration and Testing

475 development cycle for both the AGSE and ROSMOD. Because of the competition's deadlines, we
 476 focused on developing the AGSE and ROSMOD through short cycles between design, implement,
 477 test, iterate. These deadlines helped focus the core of ROSMOD's architecture towards one of rapid
 478 system design, development, and deployment.

479 Through this development cycle, our team had to maintain a balance between many (sometimes
 480 conflicting) design considerations:

- 481 • utilizing component-based design to parallelize the development effort into subunits among
 each member
- 482 • evolution of the design in concert with evolution of the implementation: must prototype and
 test quickly, but the implementation should be usable for the next phase of the design.
- 483 • track and plan for materials lead-time, and testing/integration time
- 484 • tool support, i.e. mechanical facilities and software development/testing support
- 485 • expertise required for each component/subsystem design, development, and testing
- 486 • importance of meaningful feedback especially with respect to errors and failures in
 software/hardware.

490 As in any software or hardware development, bugs and failures were encountered in the
 491 development of both the AGSE hardware and software. However, the use of the ROSMOD
 492 infrastructure allowed the causes of those issues to be narrowed down and more quickly resolved. For
 493 example, the logging and tracing framework of ROSMOD enabled the resolution of issues stemming
 494 from slow processor speed leading to long execution times. By using the logging and plotting features
 495 of ROSMOD to trace the execution time of the component operations in the AGSE software, we
 496 were able to determine that the NVIDIA Jetson was running sub-optimally, and confirmed that the
 497 CPU frequency governor was configured by default to dramatically throttle the main ARM cores

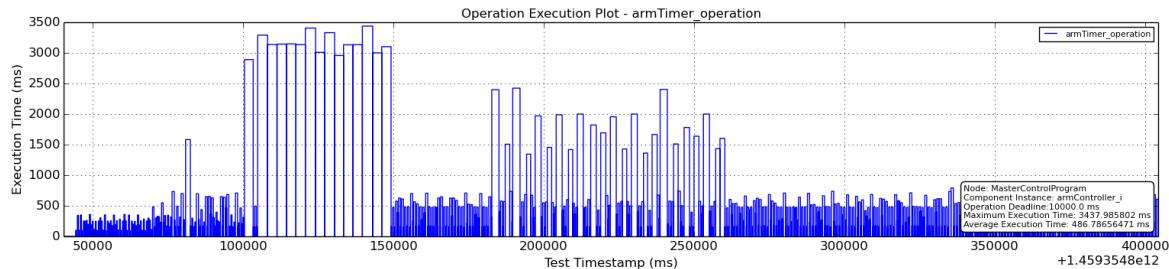


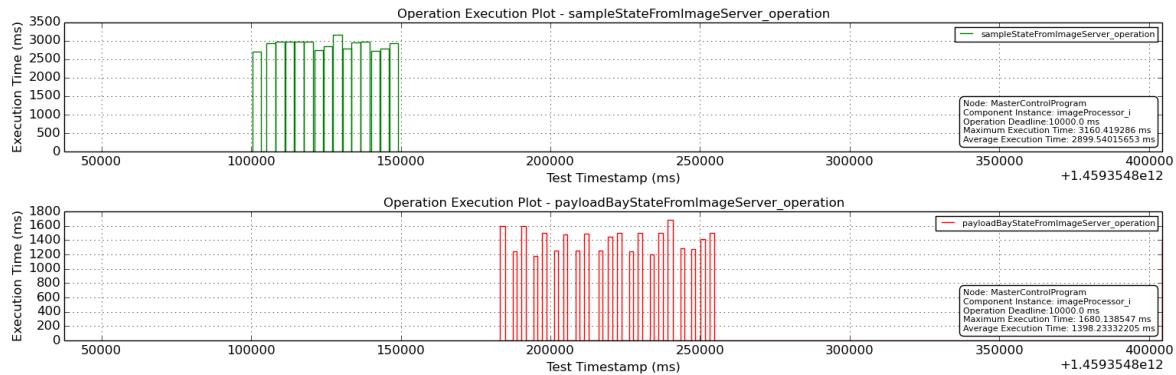
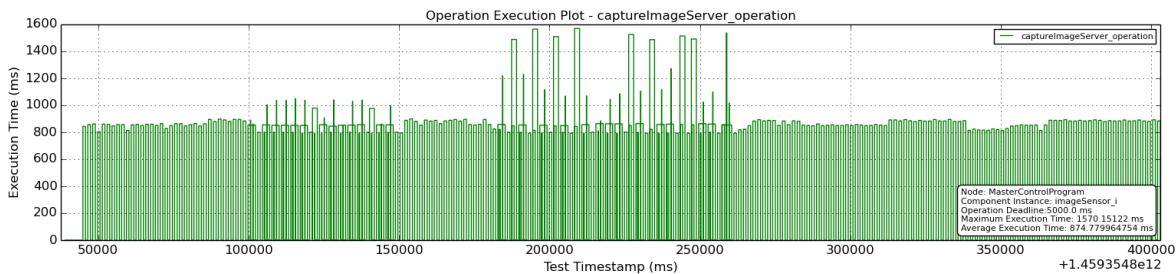
Figure 10. High-level Timer Execution

498 of the processor. Furthermore, we were able to use the logging framework to show that for some
 499 of the client-server connections in the AGSE that were configured to be persistent connections,
 500 the connection would drop immediately after being established. After determining this from the
 501 trace logs, we reconfigured those client-server connections to no longer be persistent so they would
 502 reconnect when required.

503 One of the main benefits from this timing and performance logging infrastructure was the ability
 504 to validate the periodicity of timer interactions in the AGSE. By running the AGSE software and
 505 tracking how long each operation takes, we were able to determine that the original configuration
 506 of the AGSE timers was too frequent and needed to be reduced by a factor of four. By specifying
 507 deadlines on all the operations (esp. timer, server, and subscriber) we were able to determine the
 508 bottlenecks in the system and figure out what parts of the system had deadline violations (i.e. their
 509 execution times exceeded their periodicity) and re-adjust the timers accordingly.

510 Figure 10 shows the execution time plot of the *armTimer_operation* in the high-level controller
 511 component. For sake of brevity, we avoid showing all the operational plots. In the context of
 512 Figure 7, this timer operation represents the execution of the high-level control state machine. The
 513 high-level controller communicates with multiple components over its life-span orchestrating various
 514 parts of the overall state machine e.g. initialization, sample detection, payload bay detection etc.
 515 Choosing an optimal period for this timer is necessary for many reasons. Firstly, the ROSMOD
 516 component operation scheduling is a non-preemptive one i.e. an operation must run to completion
 517 before the next request is serviced from the component operation queue. This means that if the
 518 timer operation does not complete before its period, the number of waiting requests in component
 519 queue start to monotonically rise. This hurts the system as a whole since subsequent requests take
 520 longer to complete and the high-level control breaks down. Secondly, inside the timer operation, the
 521 controller requires the services of both the motor control and the imaging components, often times
 522 via synchronous blocking interactions. This is the second cause of a potential problem as the blocking
 523 times are non-deterministic and dependent on the execution state of other embedded boards. For
 524 this reason, the AGSE software was deployed and experimented with to identify the optimal period
 525 where the response times are manageable. As shown in Figure 10, the high-level controller has two
 526 set of spikes in execution time. The first set (between 100 and 150 seconds into the experiment),
 527 as confirmed by Figure 11 corresponds to sample detection. The second set of spikes, between 200
 528 and 250 seconds, is the payload bay detection. These plots quickly present the performance of the
 529 high-level controller and the worst-case response times during periodic image processing.

530 Figure 11 presents the performance of the *GetSampleState_Server* and the *GetPayloadState_Server*
 531 in Figure 7. These servers are periodically invoked by the high-level controller during its operation,
 532 first during sample detection and then during payload bay detection. Each of these servers, on
 533 demand, are required to obtain the current camera feed from the Camera component, perform image
 534 processing, and return the results to the high-level controller. Thus, the interaction and data flow
 535 path is as follows: During sample detection, the high-level controller is periodically triggered to ask
 536 the Image Processor component to provide a new result. The Image Processor, in turn, queries the

**Figure 11.** Sample and Payload bay Detectors Execution**Figure 12.** Camera Feed Reponse Times

537 Camera component for a feed update. The Camera *ImageServer*, as shown in Figure 12 responds to the
 538 Image Processor component with a new feed. This image server is also responding to the userDisplay
 539 component that receives the camera feed to display to the user.

540 We were able to use the ROSMOD deployment infrastructure to quickly run separate
 541 experiments on the BeagleBone Blacks (single core embedded computers), testing the performance
 542 impact of running our motor control components in separate processes or as separate threads in the
 543 same process. By simply changing the deployment model and re-running the same code we were
 544 able to get ROSMOD timing and performance logs from the experiments to show the extra overhead
 545 of process-level context switching on the single-core BeagleBone Black.

546 The use of ROSMOD's performance, timing, and trace logging (coupled with the plotting utilities
 547 for those logs) enabled us to easily visually verify the behavior and performance of the AGSE software
 548 or spot anomalies when they occurred. Furthermore, the use of code-generation and automated
 549 build and deployment infrastructure meant that far less code had to be inspected for errors when
 550 a software or logical error cropped up, and the developers did not have to spend time configuring
 551 or debugging the build and deployment systems. Finally, the use of a graphical modeling tool
 552 for specifying the entire AGSE project from software to hardware to deployment enabled faster
 553 training and communications between team members as well as visual inspection of the software
 554 configuration, for instance ensuring that all required components can respond to the user's control
 555 inputs or verifying the other interaction patterns and triggering operations for each component.

556 The rapid prototyping facilitated by ROSMOD and the ROS infrastructure enabled the
 557 development of an overall *smarter* robot. The software requirements for autonomy were matched
 558 by the ROSMOD code generators such that developers had to spend little time setting up the build
 559 system and interaction patterns. The speed of development was drastically improved and the *business
 560 logic* code, i.e. the core of the implementation of the system behavior, could be made more robust in
 561 spite of the evolution of and inclusion of more autonomy.

562 5. Materials and Methods

563 This section covers the materials and methods for ROSMOD and the AGSE, both what was used
 564 in the competition (2014-2015) as well as the current state of each.

565 5.1. Competition AGSE

566 The version of the AGSE software and hardware designs that were used in the 2014-2015 NASA
 567 SLI competition can be found open-sourced online[15]. The current version of the AGSE code and
 568 hardware designs has been moved and can be found in the Vanderbilt Aerospace Design Lab's AGSE
 569 repository[16].

570 5.1.1. Kinematics

571 The AGSE is a 4-DOF robot utilizing a revolute base joint to rotate the robot body, two prismatic
 572 joints to move vertically and horizontally, and a final revolute joint providing an orienting wrist for
 573 the end effector. A wireframe and workspace rendering of the AGSE can be seen in Figure 13.

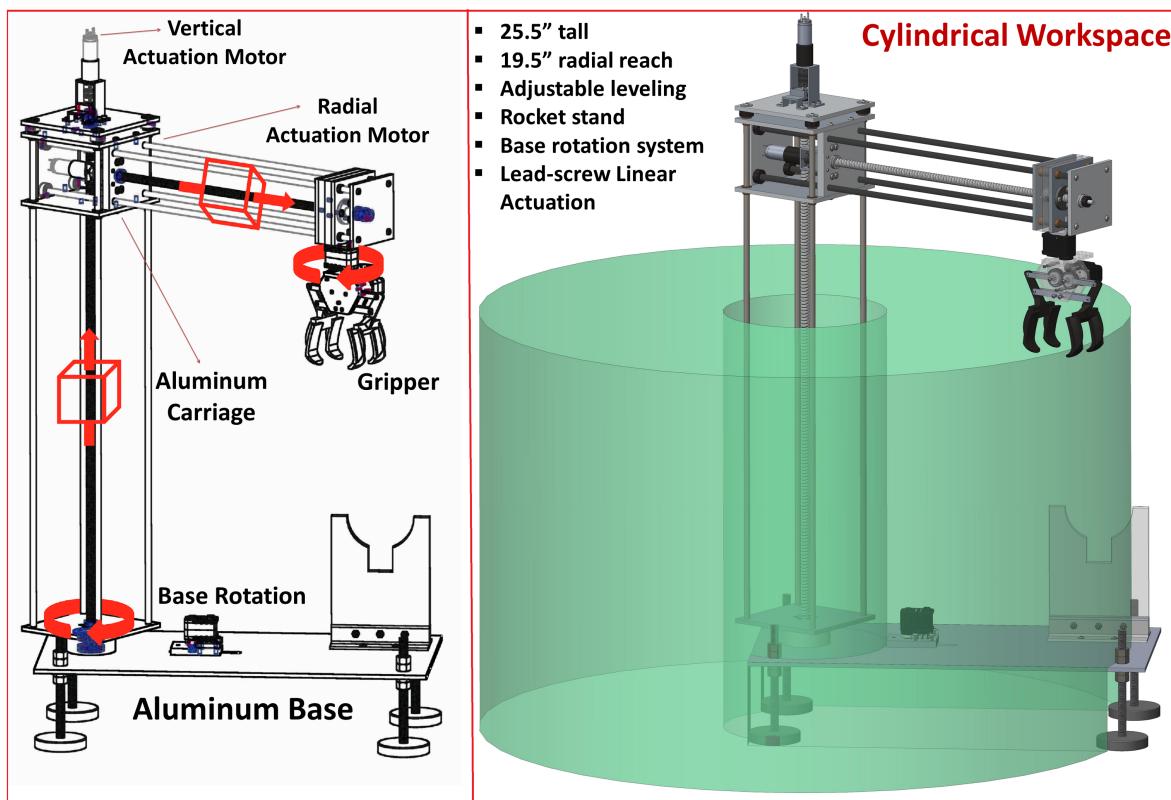


Figure 13. AGSE Mechanical Design

574 By design, the single revolute and two prismatic joints of the AGSE provide the basis for a
 575 cylindrical coordinate system and workspace, reducing the implementation of both forward and
 576 reverse kinematics to a trivial exercise of mapping joint position to the corresponding coordinate
 577 in the workspace.

$$\begin{bmatrix} \theta_{workspace} \\ \mathbf{r}_{workspace} \\ \mathbf{z}_{workspace} \end{bmatrix} = \begin{bmatrix} \theta_{rev} \\ \mathbf{r}_{pris} \\ \mathbf{z}_{pris} \end{bmatrix}$$

578 5.1.2. Structure

579 The AGSE base is comprised of a machined sheet of aluminum upon which leveling legs are
580 mounted to easily account for uneven surfaces. Protruding from the base is the revolute joint, a
581 machined spindle centered within ball bearing cup. Extending upwards along this rotational axis
582 is the vertical join, a lead screw and guide rod assembly driving an aluminum carriage. A similar
583 lead screw-carriage assembly extends from the side of the vertical carriage to provide motion within
584 the horizontal plane. A mounting point for both the gripper and camera hangs from this horizontal
585 carriage.

586 Underneath the base is a platform for mounting batteries, power regulation and protection
587 circuitry, and on-board computer systems. At the top of the vertical assembly is a mounting point
588 for the actuator control electronics.

589 5.1.3. Actuation and Sensing

590 A Dynamixel MX-28T servo is mounted to the revolute joint's spindle to provide rotational
591 movement. Two additional Dynamixel AX-12 servos are used to orient and actuate the gripper. The
592 two lead screw assemblies are driven using 12 V Faulhaber motors mounted directly to the lead
593 screws.

594 The AGSE guides the end effector motion using the limit switch-encoder combo on its linear
595 actuators, the built in positional feedback from the servo motors, and the optical feedback provided
596 by a camera mounted above the end effector (allowing the AGSE to recognize objects within the
597 reachable area underneath the gripper phalanges). Limit switches are mounted at the minimum
598 and maximum of each lead screw assembly's range of movement, providing hard stops to motor
599 actuation. Quadrature encoders are then used within this range of motion to monitor the position of
600 the vertical and horizontal carriages. The Dynamixel servos controlling the revolute joint and gripper
601 provide position and speed feedback, as well as PID tuning to allow for quick and responsive control.

602 5.1.4. Power System

603 The power from the AGSE comes from two 12V 12Ah lead-acid batteries in series, which provide
604 input power to a 12V power regulator. The 12V output from the power regulator passes through
605 a relay which is controlled using a key-switch on the User Interface Panel (UIP). From the relay
606 the 12V runs in parallel to the NVIDIA Jetson TK1, the Motor Control Cape on the Motor Control
607 BeagleBoneBlack, the User Interface Panel power control cape (a stripped down version of the Motor
608 Control Cape with the H-Bridges and other motor related electronics not populated), and finally to the
609 ethernet switch which provides a closed, hard-wired LAN for communications between the boards.

610 On the Motor Control Board, the 12V input drives 1) the cape's 5V regulator which provides
611 power to the BeagleBone Black and the encoders, 2) the 12V Dynamixel servo motors, and 3) the
612 H-Bridges for the two 12V linear actuators.

613 On the UIP, the 12V simply powers the 5V regulator which provides power to the BeagleBone
614 Black, the touchscreen LCD, and the display LEDs.

615 5.1.5. Control

616 The payload bay and nose section of the rocket rests on the base of the AGSE. This payload bay is
617 motor-controlled by the high-level controller. When the AGSE starts up, the payload bay's on-board
618 Arduino motor controller is commanded to open the nosecone. Once open, the AGSE performs an
619 initialization routine. This routine includes movement of the vertical and radial actuators to a safe
620 height and a retracted state. Then, the AGSE rotates on its base to a servo angle of zero degrees.
621 Once this routine is complete, the robot begins searching for the sample. The camera used for this
622 purpose is a 1920x1080 wide resolution feed; one that enables the robot to sweep wider distances

when searching for the sample and increases the step size of the search i.e. the search steps up by 20 degree increments while searching for the sample.



Figure 14. AGSE Sample Detection - Periodic Image Processing

Periodic sample detection performed by the AGSE uses OpenCV-based image processing algorithms to identify and track the sample in real-time. An Image Processor component periodically fetches the latest feed from the mounted camera and performs a series of filtering tasks. Each *RGB* (Red-green-blue) image frame is converted to both *HSV* (Hue-Saturation-Value) and *Grayscale* image frames. After applying thresholds, filters, erosion and dilation methods, the target sample is extracted from the webcam feed. Once the target sample is detected, as shown in Figure 14, we draw contours around the object and identify its relative position and orientation.

Once the sample is detected, the AGSE records the position and orientation of this sample and begins searching for the payload bay. The payload bay is detected using marker detection methods. Coded markers are stuck on the payload bay to detect the angle at which the sample needs to be dropped into the bay. As shown in Figure 15, by processing the input camera feed, the two markers on the bay are detected and the angle of drop is calculated.

Once the sample and payload bay are fully detected, the AGSE performs a simple pickup-drop transition where it rotates to the position of the sample, grabs the sample, rotates to the position of the payload bay and drops the sample in the bay. The arm control logic also sends a "Close Payload Bay" command that actuates the payload motor and closes the nosecone, effectively completing the sample retrieval process.

5.1.6. Communication

The AGSE communicates between its various subsystems using a few different protocols. At the high level, the different control boards of the AGSE communicate using ROS over a wired ethernet LAN. On the motor control board, the servo motors are directly connected to a 3.3V serial port on the GPIO pins of the BeagleBone Black. Because the servo motors communicate at 5V using a 1-wire communications line, the communications transmitted to the servos from the BeagleBone Black passes through a buffer implemented with NPN transistors. Because the servos can be daisy-chained, only one connection is made to the Motor Control Cape and each servo is connected in series through the previous servo. This daisy-chaining greatly simplifies the wire routing and increases the modularity and maintainability of the AGSE motor hardware. Finally, the NVIDIA Jetson

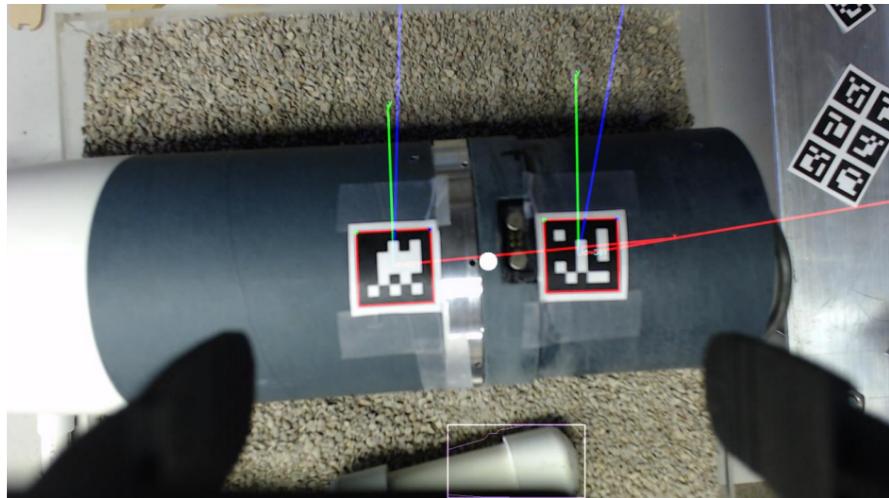


Figure 15. AGSE Payload Bay Detection

652 communicates to the Payload Bay Arduino to open and close through its own USB port acting as a
 653 virtual serial port. This serial connection is implemented as a quick-disconnect USB cable connected
 654 to a port on the surface of the rocket.

655 5.2. AGSE Changes Since the Competition

656 Post competition, minor mechanical and electrical improvements were made to the AGSE. A new
 657 mounting bracket was machined to replace the temporary mounting of the Dynamixel MX-28T that
 658 occurred the day of the competition. A new undercarriage made of extruded 20mmx20mm aluminum
 659 was fabricated to house the on-board power circuitry and embedded systems. Additionally, new
 660 power protection circuitry was made in the form of fuse boards and a dedicated emergency stop
 661 button in lieu of the key switch in the UIP.

662 5.3. Competition ROSMOD

663 ROSMOD exists as two separate code-bases: 1) the ROSMOD component model
 664 implementation, which enables the configuration of the component operation queue to support
 665 different scheduling schemes and priorities/deadlines for operations, and 2) the ROSMOD graphical
 666 modeling, generation, and deployment tool suite. These two code-bases are referred to as
 667 ROSMOD-COM and ROSMOD-GUI, respectively. All ROSMOD related code (old and new) can be
 668 found open-sourced online in the ROSMOD Github organization[17].

669 ROSMOD-COM is a package which extends the functionality of the *ROS Callback Queue* into
 670 which timer, subscriber and service operations are placed. To enable the addition of scheduling,
 671 priority, and deadline attributes to operations in the queue, all the relevant objects were modified,
 672 e.g. Timer, Subscriber, etc. Additionally, the queue was extended to support priority insertion of
 673 operations based on their deadline (EDF scheduling) and priority (PFIFO). By using the relevant
 674 classes and methods from ROSMOD-COM, ROSMOD components can ensure the proper scheduling
 675 of their operations.

676 The version of ROSMOD that was used in the competition can also be found open-sourced
 677 online[5], as the *v0.3-beta* release. Note that the version of the ROSMOD-GUI that was used is under
 678 the *gui* folder and is a Python-based program for which the relevant dependencies must be installed
 679 following the *README*. This is one of the primary problems with this version. Firstly, ROSMOD
 680 requires Linux and the Python programming language and a long list of dependencies. Also, this
 681 version, as used in the competition was primarily used for code generation and compilation. The
 682 deployment framework had several shortcomings, primarily due to the metamodeling language at

683 the time. Many of these shortcomings have now been addressed e.g. the concept of an experiment, a
684 much improved network model etc.

685 *5.4. ROSMOD Changes Since the Competition*

686 The current version of ROSMOD is split into two separate repositories under the ROSMOD
687 organization: the new version of the GUI[18], and the current version of ROSMOD-COM[5].

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696 **Author Contributions:** Gabor Karsai conceived and designed the ROSMOD component model. Pranav Srinivas
697 Kumar and William Emfinger were the primary software developers for the ROSMOD toolsuite, the ROSMOD
698 component model, and the AGSE control software. Amrutur Anilkumar and Benjamin Gasser designed the
699 AGSE robot and lead the Vanderbilt Aerospace Design Laboratory. Dexter Watkins, and Benjamin machined
700 and constructed the AGSE robot. William Emfinger performed the AGSE execution time experiments. Pranav
701 Srinivas Kumar analyzed the data and generated execution plots. Pranav Srinivas Kumar, William Emfinger and
702 Dexter Watkins wrote the paper.

703 **Conflicts of Interest:** The authors declare no conflict of interest. The founding sponsors had no role in the design
704 of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the
705 decision to publish the results.

706 **Abbreviations**

707 The following abbreviations are used in this manuscript:

- 708
709 AGSE: Autonomous Ground Support Equipment
710 ARM: Advanced RISC Machines
711 BBB: Beaglebone Black
712 CNC: Computer Numerical Control
713 CPS: Cyber-Physical System
714 CPU: Central Processing Unit
715 CUDA: Compute Unified Device Architecture
716 CV: Computer Vision
717 DARPA: Defense Advanced Research Projects Agency
718 DOF: Degrees of Freedom
719 EDF: Earliest Deadline First
720 FIFO: First-In First-Out
721 GPIO: General Purpose Input/Output
722 HSV: Hue-Saturation-Value
723 IP: Internet Protocol
724 LAN: Local Area Network
725 LCD: Liquid Crystal Display
726 LED: Light Emitting Diode
727 MAV: Mars Ascent Vehicle
728 NASA: National Aeronautics and Space Administration
729 PFIFO: Priority First-In First-Out
730 PID: Proportional-Integral-Derivative
731 QEP: Quadrature Encoded Pulses
732 RGB: Red-Green-Blue

733 RMI: Remote Method Invocation
734 RML: ROSMOD Modeling Language
735 ROS: Robot Operating System
736 SFIO: Special Function Input/Output
737 SSH: Secure Socket Shell
738 SLI: Student Launch Initiative
739 UAV: Unmanned Aerial Vehicle
740 URL: Uniform Resource Identifier
741 UUV: Unmanned Underwater Vehicle
742 UIP: User Interface Panel
743 USB: Universal Serial Bus
744 XML: Extensible Markup Language
745

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