1 Introduction

Robotic systems are an important class of cyber-physical systems. The ability of robots to interact intelligently with the world rests upon embedded computation and communication, real-time control, and perception of the world around them [1]. Integration of sensors and actuators into a single cohesive robotics system often requires a composition of service-based components that either produce, consume or transform information in a loosely coupled, parallel manner.

Although robot controller developers can create a program to execute directly on a specific robot platform, frameworks are more often used as an intermediary between autonomous controllers and the hardware. Controllers access and manipulate robots via application programming interfaces (API) that reflect a generalized model of the robot. The APIs access robot-specific interfaces through device drivers. This approach not only speeds development through reuse of code (code is not hardware specific) but also facilitates the re-purposing of controllers to other hardware platforms. Device drivers in this context act as a mechanism for mapping individual robot features to domain concepts. Device drivers are usually implemented as processes that manage the hardware connection for the framework while translating requests for data and action from the framework into formatted message requests and responses. Although some increases in latency are experienced with multiple levels of indirection, it is often considered trivial compared to the time investment of attempting to develop and debug remote applications or retrofitting algorithms for varying hardware platform configurations.

There are some opportunities inherent in this approach. Some would say that device driver development is complex. It is probably true that writing reasonable performing device drivers (like all embedded development) requires an understanding of hardware, timing issues, threading, process synchronization, performance tuning and the operating system of the driver host system. However, good examples exist within frameworks and development of reasonable drivers is not prohibitive in terms of skill set. A more pressing issue concerns the multiplicity involved in creating device drivers. As device drivers provide a programmed link between hardware and frameworks, custom drivers have to be created for each framework hardware pair. Although some robot frameworks enjoy more popularity than others, many frameworks are routinely used within the robotics research and education community. An additional challenge is that while there are groups that focus on framework development, in house driver support for existing platforms is usually limited to a few popular platforms and certainly does not include any custom platforms or configurations. Robot manufacturers typically provide device drivers for a subset of "supported" frameworks.

Addressing the issue of needing one-to-one mappings between frameworks and devices can introduce some efficiencies and additional flexibility that robotics developers do not currently have. However there is a bigger issue at stake. Although there are many innovations from software engineering that have been utilized successfully within robotics architectures, there is a notable exception when it comes to identifying the system of record for device syntax and semantics. In the context of robotics, it is this failure that results in major duplication in integrating hardware devices into autonomous controllers. Moreover the more important opportunity in making the hardware the system of record for its syntax and semantics is the ability to discover services and provide a component wrapper around devices that allows for composition of intelligent software.

RDIS (Robot Device Interface Specification) [2] is a domain-specific language (DSL) that captures the syntax and semantics of hardware devices with embedded controller managed external interfaces. This declarative description captures the manufacturer invariant interface made available by firmware in terms of transports and messages and how they map to domain specific concepts. RDIS is currently a preliminary prototype that supports a limited set of processing models and domain concepts. The work proposed as part of this effort will accomplish the following major innovations to RDIS as a contribution to the engineering of cyber-physical systems: 1) extend the actuation model to include a larger set of **popular kinematic chains** from both manufacturing and exploration robotics, 2) extend the processing models to include a larger set of **execution semantics**, and 3) create a supporting set of tools and frameworks that supports **prototyping, evaluation and adoption**.

Hardware that can communicate its capabilities and programming API to a general programming tool would offload the knowledge of the hardware to the system of origin (the correct system of record). This aspect of the proposed project is **transformative** and directly impacts the **engineering of cyber-physical systems**; it could potentially affect the creation of new hardware platforms, reduce the complexity of device drivers (encourage new devices) and lower the learning curve to working with platforms. This project accomplishes a **breakthrough** using the intersection of software engineering and embedded systems. RDIS describes available services much like web-based services while also providing transport and timing specific details. While this breakthrough proposal concerns itself primarily with robotics devices (those that provide sensor information or actuation), it is expected that the process and principles developed here will be generalizable to sensors and actuators in other domains (i.e. car sensors, etc). Interactive design has bought new energy and rigor to fabrication and hardware prototyping. Incorporating interactive design principles into robotics software tools would encourage software prototyping and experimentation, providing learning experiences in computational thinking, computer science and robotics.

2 Background

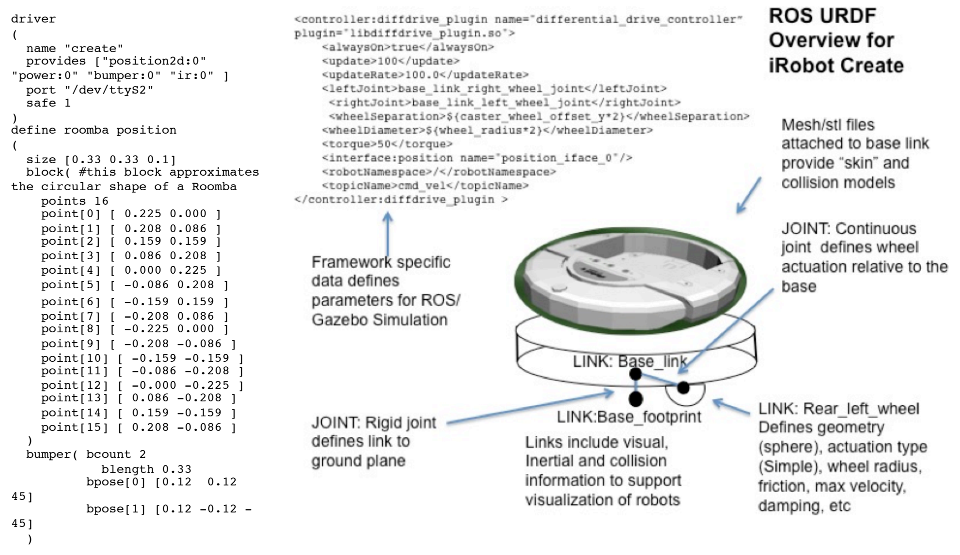
2.1 Domain modeling of Robot Hardware and Model Metrics

Not too surprisingly, the Object Management Group (OMG) has taken an interest in standardizing the domain of robotics in the establishment of the Robotics Domain Task Force (RDTF) [3]. They have a small set of platform independent models (PIM) and platform specific models (PSM) [4, 5, 6] for robotics defined in terms of UML. None, however, focus on the modeling of the kinematics and dynamics of robots. The researchers in [7, 8] used Eclipse Modeling Framework to deploy application software to different device-framework pairs. One [7] used models for a P3DX robot and a QFIX-based robot to for several different platforms, including Player, Microsoft Robotics Studio, and SmartSoft [9]. Statecharts [10] were used to define robotic behavior. The other [8] proposed SMARTMARS, a meta-model derived from SMARTSOFT to use for modeling and analysis of robots. A separate researcher [11] used a similar approach to build a subsumption-based robot architecture which was deployed to a NXT Mindstorms robot. These approaches represent an alternative to working directly in a domain-specific language, instead relying on well-understood standards like UML. There are some drawbacks to this approach as at least some textual representation is still needed for the model to be serialized and passed over the network. As well, textual representations tend to simplify visual models as they do not need to include user interfaces aspects of visual models such as the position of a model element on the computer screen. However, structured visual formalisms may be compiled into a domain-specific language which could turn out to be a preferred way to model particular robots.

A secondary goal for this project will involve evaluating the proposed model in reference to other existing models and to assess the progress of the model as it grows in the long-term. Therefore, one shall define a set of metrics to assess model growth and quality, and possibly also the size in relation to other models (other models in this case being the implied models used by the aforementioned frameworks). To achieve a reference frame for how this might be accomplished, a short literature review was conducted on the current view of metrics at the model level, useful for this project. Mohagheghi presents a survey of the state of model metrics as a part of an ongoing research effort in model quality metrics

[12]. The paper presents six general goals for measurement at the model level which should serve as the inspiration for the metrics used to evaluate a model. The ideas of Lange on model size [13] are also presented, in particular dealing with UML models. Lange proposes a specific metric for UML relative size, which could be used to measure the size of the proposed robot model against existing description models. In [14], the authors present their perception of model metrics for DSLs, offer a classification of the types of effort they believe are encountered when working within a domain-specific model (DSM), the two basic types being Development Effort and Runtime Effort. Within the context of this project, the metrics which measure Development Effort are most interesting, particularly those which measure Modeling Effort, the effort involved in developing a DSML model, and Cognitive Effort, the cognitive effort required to do so. They use a weighted sum to approximate the size of a model as a means to measure modeling effort. This metric should be fairly sufficient for calculating an inexact model size, and it should translate well between different models. Another interesting metric they use is the closeness of mapping ratio (COMR) which they used the ratio of the number of problem-level language primitives to the number of solution-level primitives which do not have mapping to the problem domain. This metric is interesting because it provides insight to the disconnect between the problem domain and the solution domain. However, to actually implement this metric would require a classification of any existing language to be benchmarked against and could be expensive time-wise. The authors also mentioned other metrics which are useful when evaluating imperative languages, however this project will focus on building a declarative language so they will not be so directly applicable. The author in [15] considers a new approach to estimating a model complexity via the analysis of the meta-model which defines it. This could solve the problem of evaluating complexity in a purely declarative model like RDIS.

2.2 Hardware descriptions in existing frameworks



```
driver
(
  name "create"
  provides ["position2d:0"
"power:0" "bumper:0" "ir:0" ]
  port "/dev/ttyS2"
  safe 1
)
define roomba position
(
  size [0.33 0.33 0.1]
  block( #this block approximates
the circular shape of a Roomba
    points 16
    point[0] [ 0.225 0.000 ]
    point[1] [ 0.208 0.086 ]
    point[2] [ 0.159 0.159 ]
    point[3] [ 0.086 0.208 ]
    point[4] [ 0.000 0.225 ]
    point[5] [ -0.086 0.208 ]
    point[6] [ -0.159 0.159 ]
    point[7] [ -0.208 0.086 ]
    point[8] [ -0.225 0.000 ]
    point[9] [ -0.208 -0.086 ]
    point[10] [ -0.159 -0.159 ]
    point[11] [ -0.086 -0.208 ]
    point[12] [ -0.000 -0.225 ]
    point[13] [ 0.086 -0.208 ]
    point[14] [ 0.159 -0.159 ]
    point[15] [ 0.208 -0.086 ]
  )
  bumper( bcount 2
            blength 0.33
          bpose[0] [0.12  0.12
45]
          bpose[1] [0.12 -0.12 -
45]
  )
```

```
<controller:diffdrive_plugin name="differential_drive_controller"
plugin="libdiffdrive_plugin.so">
    <alwaysOn>true</alwaysOn>
    <update>100</update>
    <updateRate>100.0</updateRate>
    <leftJoint>base_link_right_wheel_joint</leftJoint>
     <rightJoint>base_link_left_wheel_joint</rightJoint>
     <wheelSeparation>${caster_wheel_offset_y*2}</wheelSeparation>
    <wheelDiameter>${wheel_radius*2}</wheelDiameter>
    <torque>50</torque>
    <interface:position name="position_iface_0"/>
    <robotNamespace>/</robotNamespace>
    <topicName>cmd_vel</topicName>
</controller:diffdrive_plugin >
```

ROS URDF Overview for iRobot Create
Mesh/stl files attached to base link provide "skin" and collision models
JOINT: Continuous joint defines wheel actuation relative to the base
Framework specific data defines parameters for ROS/ Gazebo Simulation
LINK: Base_link
LINK:Base_footprint
JOINT: Rigid joint defines link to ground plane
Links include visual, Inertial and collision information to support visualization of robots
LINK: Rear_left_wheel Defines geometry (sphere), actuation type (Simple), wheel radius, friction, max velocity, damping, etc

Figure 1: Sample device descriptions within frameworks.

Many frameworks use a declarative description of the robots. Player/Stage [16] is both a 2D simulator and a robot control framework. Robot description files are broken into two pieces: 1) a 2D description of the robot and its sensors(Figure 1: right) and 2) a set of interfaces that abstract the data produced by hardware to a standard format. The description, used for simulating the robot, consists of a polygon-based footprint with sensor locations marked. Actuation and sensor characteristics along with parameters for simplified error models are used to complete the model of the robot. A domain-specific set of classes and message types describe what data can be obtained or how the robot can be manipulated including position (pose2d) and distance to other objects (single point is range, multipoint is laser). The classes and message types represent the interface that abstracts the robot hardware to the data that it can produce or consume. Writing software to the interfaces that a robot can utilize (rather than the specific robot) allows software to be written either for a simulated robot or a real robot, which in turns eases the transition from simulation to physical implementation.

ROS [17] targets a 3D simulation framework (Gazebo) and more sophisticated intelligent controller, which require a more rigorous description. UDRF (Uniform Robot Description Format) provides a 3D physical description broken into links and joints to facilitate not only mobile robots but manipulators as well (Figure 1: right). Geometric bounding boxes and meshes allow for collision detection and realistic visualization. Like Player Stage, ROS utilizes a message-based model to decouple data providers from data producers. Ideally robots that provide and consume similar data types can be controlled similarly. Unlike Player Stage, URDF not only serves as a mechanism for simulating robots but also allows for the visualization of real robots in both real-time and off-line (through saved messages).

URBI [18] is a domain specific language for robot applications. It is a platform which controls robots. Its language, urbiscript, has native syntax for parallel and event-driven constructs. This gives it high expressivity for solving problems common in robots. As an example, urbiscript can easily natively express "when my left arm stops moving, start moving the right arm." However, the limitation in URBI is that it is another platform. It expects that the "UObject" needed to control the robot exists. Also, URBI focuses only on robotic control, however it can tie into simulators to be used as a control module for the simulation.

The authors in [19] present a domain specific language for the control of a novel robot. The ATRON self-configurable robot is composed of several independent modules which can be assembled in different manners to create a robot whose function changes according to how the modules are connected. They use the example of a car configuration in their paper. Their language is role-based, meaning a module can deduce its role by examining its own connectivity. The advantage to this type of description is that it allows the reuse of one behavior description for several configurations of ATRON modules. For example, a description file that represents a car may be used for four-wheel or six-wheel configurations. This is an interesting abstraction for application code, however it has the same problem as URBI, in that a platform-specific module must be created so that a robot may communicate with the framework. Although the literature reveals very few attempts at using DSLs for hardware device drivers, Thibault et al report the creation of efficient video device drivers using a novel DSL [20].

A select number of robot control frameworks move beyond visualization information and relevant interface declaration in the hardware description. PREOP, an Alice-based programming interface [21, 22, 23] for robots takes this paradigm further. Not only is 3D visualization information supplied but also the programming interface is completely specified by the selection of the robot object. This is accomplished by linking the real-time control mechanism and exposed API available to the user within the robot object.

All robotic architectures require that the user provides information regarding the target hardware devices and the resulting data at development time in absentia of the hardware. Two problems result from this process: 1) users must understand the hardware and resulting data and 2) encode the hardware details properly in the framework of choice. A mechanism that provides the user with the details of available resources could remove this step and the associated issues with attempting to properly characterize the hardware. More importantly, self-describing hardware could lessen both frustration and the need for in-depth hardware knowledge on the part of the user.

2.3 RDIS (Robot Device Interface Specification)

We propose a new paradigm where knowledge of the hardware mechanism is embedded in the hardware, rather than declared in software. RDIS (Robot Device Interface Specification) has three purposes: 1) provide enough information for simulation and visualization of hardware and controllers, 2) declaratively specify the mechanism for requesting data and actuation, and 3) inform users of standard message types that can be obtained from the hardware to facilitate connection to existing frameworks through discovery. The challenge in successfully defining the RDIS is in creating a model that captures the generalizable aspects of robots and provides a mechanism to specialize the aspects that vary.

RDIS relies upon the relatively invariant nature of mobile robots. Although some robots are built for a specific task, general use robots within education and research communities tend to leverage designs that provide closed loop inverse kinematic solutions; differential drive being part of this class of robots. In addition, many robots including the popular Mobile Robots Pioneer class, iRobot Creates, K-Team robots, Erratic ER-1, White Box Robotics Model 914, Ar.Drones, and BirdBrain Finches contain an embedded firmware controller that accepts commands via a serial, Bluetooth, WiFI or USB interface rather than require the users to download a program to onboard memory. Even robots that require a local software program to run have modes where the local software program presents an API to an external computer (i.e. Lego Mindstorms via Lejos and E-Puck). In both of these cases, the users create an autonomous controller program that communicates with the firmware to affect actuation and to obtain sensor information.

The RDIS specification can be defined as DSL that is used to program robots at a higher, domain-specific level. In the application of robots, the existence of firmware (not programming hardware directly) simplifies the process. Designing a declarative specification for robot hardware requires a solid domain model of the hardware connection and services that are provided. Domain models, when designed properly, can be somewhat invariant to changes and can provide a stable basis for deciding the structure and parameters of the specification.

The preliminary artifacts generated in this approach include RDIS specifications and grammars that generate a command line program and a ROS driver [2]. The initial scope of this research focuses on a set of domain concepts that represent popular platforms and devices and therefore are present in most frameworks as an abstraction. The current set of domain concepts include DIFFERENTIAL DRIVE and RANGE. Differential drive robots (robots with two opposing wheels on a single axis) are controllable using linear and rotational velocity. Acknowledging differential drive explicitly allows for an easier parameterization through state variables that denote odometry resolution, wheel size, offset of axis and wheel base. While some frameworks explicitly recognize differential drive as a kinematic design (Player), others group all platforms under a single fully expressive interface where the user must know which dimensions are controllable. For example, within the ROS system, a TWIST message type is used to provide control commands to a differential driver robot through linear and angular velocity. The ROS template (discussed in more detail in [2]) maps each domain concept to the appropriate programming paradigm, which in this case is a subscription to the TWIST message and a callback handler that contains the code to map the TWIST message parameters to the SETSPEED firmware primitive. A preliminary RDIS has been implemented for the Finch robot from Bird Brain and the K-Team Koala[2]. In this design, a JSON-based description file is used (although any syntax can be used including XML). The intermediate product is an abstract syntax tree that represents the robot details in a domain specific model. This intermediate format can be further processed to verify conformance to the specification. End products such as framework specific device drivers or stand-alone servers are generated from the verified syntax tree using templates that format data based on the model.

3 Research Plan

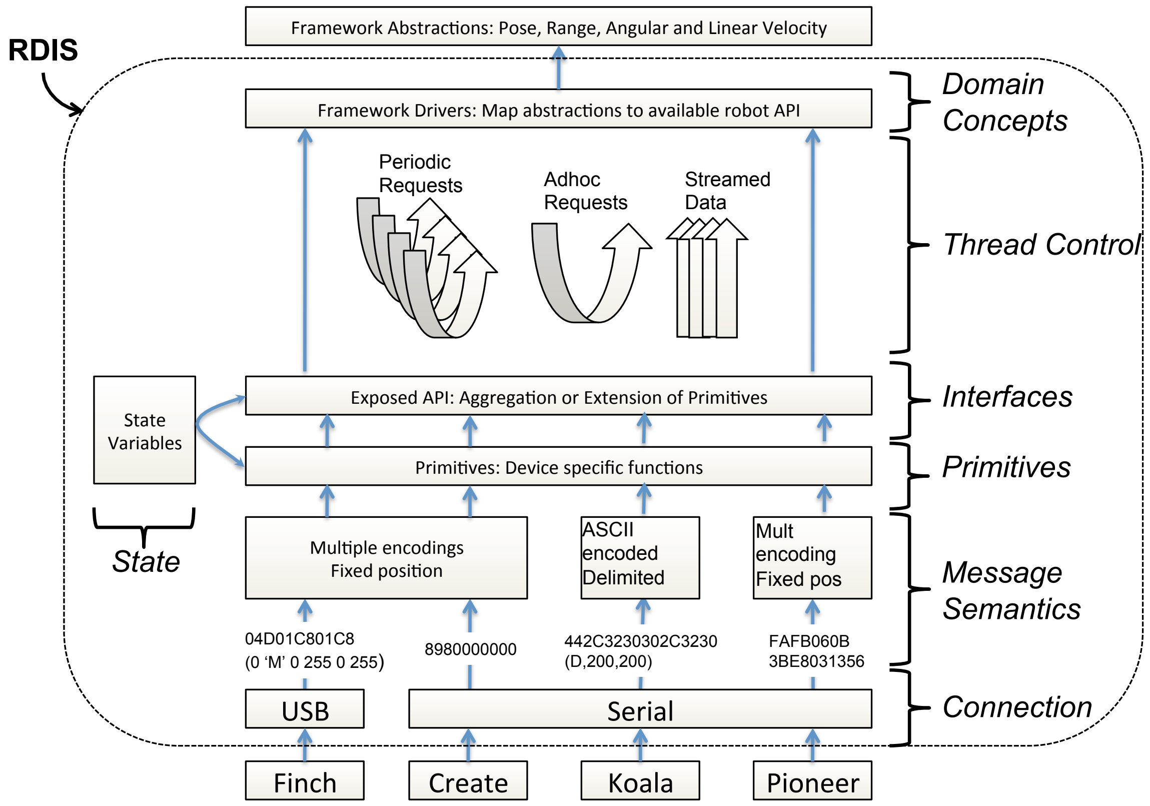

Framework Abstractions: Pose, Range, Angular and Linear Velocity
RDIS
Framework Drivers: Map abstractions to available robot API
Domain Concepts
Periodic Requests
Adhoc Requests
Streamed Data
Thread Control
State Variables
Exposed API: Aggregation or Extension of Primitives
Interfaces
Primitives: Device specific functions
Primitives
State
Multiple encodings Fixed position
ASCII encoded Delimited
Mult encoding Fixed pos
Message Semantics
04D01C801C8 (0 'M' 0 255 0 255)
8980000000
442C3230302C3230 (D,200,200)
FAFB060B 3BE8031356
USB
Serial
Connection
Finch
Create
Koala
Pioneer

Figure 2: Preliminary domain model for mapping devices to frameworks [2].

The preliminary result supports the idea that general robot devices can be described declaratively in a manner that supports discovery and that links to the back-end processes. RDIS must be expanded to be useful for a larger pool for robot platforms and frameworks. The work proposed as part of this effort will accomplish the following major innovations to RDIS as a contribution to the engineering of cyber-physical systems:

1. Extend the actuation model to include a larger set of popular kinematic chains from both manufacturing and exploration robotics, and
2. Extend the processing models to include a larger set of execution semantics,
3. Create a supporting set of tools and frameworks that supports prototyping, evaluation and adoption.

3.1 Expansion of domain concepts to additional kinematic chains

Domain concepts map interfaces to domain-specific concepts in a framework agnostic manner. Each framework has a notion of a general set of abstract data types generated from device drivers such as pose estimates, pose relative to an identified landmark, control via linear and angular velocity along a dimension or axis, and point and fields of open distance. The DOMAIN CONCEPTS definition identifies

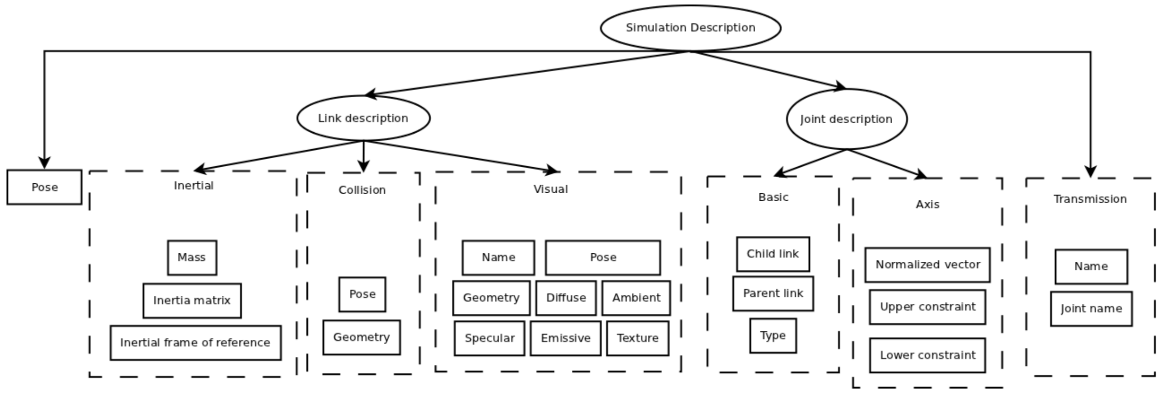


Figure 3: General model for describing kinematics, appearance, collision and dynamics parameters sufficient for simulation. Currently targeted platforms include Gazebo, Webots, and ROS.

interfaces that map to the abstract concepts allowing for templates to map the abstract concepts to the existing interfaces available on a device.

From the previous sections it is apparent that the robot kinematic modeling languages are missing necessary components for a generalized description for use in simulation. Some description formats do well in defining the geometries of the robot, but make categorical assumptions about the kinematics of the robot, offloading the actual kinematic description to the framework itself. As an example, Stage has a drive “diff” statement to label a position element as having differential-drive steering, and Webots has a DifferentialWheels node which acts as the base node of a robot description having differential steering. URDF solves this by defining a relationship between transmissions and joints, but its approach is specific to the PR2 robot.

Current models of kinematics are adept at modeling the construction of the robot in a way that is almost a standard. However, what is missing between all of them is how to model controllable joints. If a solid mapping can be defined between programming interfaces and resultant efforts at joints, this would benefit the robotics community greatly as there is not currently a description format which does so without the aid of a companion plugin or hardware description. RDIS would benefit much from this component as well as it would define the bridge between the control model introduced in earlier work [2] and the kinematic model which it currently lacks. Thus, the work that needs to be done is to define RDIS’s kinematic model according to the trends seen from other frameworks and then provide a mapping from interfaces in the control model to transmission efforts at joints in the kinematic model. It is clear that a viable robot kinematic model will somehow take heed of some of the existing description formats to ensure there is sufficient compatibility with the model. The problem lies in deciding which parameters are essential to a proper kinematic modeling and which are parameters which lose meaning when carried to other frameworks. An additional goal is to find a concise set of these parameters such that no one parameter may be defined in terms of other parameters.

Figure 3 details the concepts in the updated working model for expanded kinematics. LINK and JOINT are composed from similar concepts in existing frameworks and simulation descriptions. The LINK is an atomic rigid body in the robot’s structure which constitutes the majority of the robot’s composure by mass. A link is a primary parameter to the physics simulation as it contains the parameters necessary to simulate the physics of a robot. Additionally, a simulator typically has a visual representation of the robot to present to the user and a LINK will represent the majority of the visualization, so there will be parameters which are to be used by the simulation renderer. Finally, as the LINK is the only material component in the robot model, it will serve as the basis for the collision model, so the parameters to the collision engine must also be defined.

The JOINT component of the model characterizes a set of constraints imposed on two joints. In this relationship, there is strictly one related parent LINK and one child LINK. There are six degrees of freedom between two unconstrained links, and a joint restrains one or many of them. The standard degrees of freedom are X, Y, Z, roll, pitch, and yaw. From the examined frameworks, three main types of joints reappear between frameworks, all of which JOINT generalizes a prismatic joint constrains all degrees of freedom except for Z. This allows child link to translate freely in one dimension with respect to the parent link's frame. By convention, this is normally the Z-axis in joint space. This type of joint might be used to model a gripper for a robot arm. A hinge joint constrains all degrees of freedom except for pitch. This allows a link to rotate in one dimension about a single point of rotation with respect to its parent link's frame. This type of joint might be used to model a fixed wheel on a differential drive robot if no bounds were posed on the joint rotation. A ball-and-socket joint constrains X, Y, and Z. This allows for rotation of a link about any of its axes with respect to its parent link. This type of joint might be used to model a spherical caster wheel for a differential drive robot.

A TRANSMISSION component is not yet well-defined in the current state-of-the-art in robot modeling, therefore it may contain some parameters which are to be discovered. From the previously discussed frameworks, URDF was the only description format which included this component, which the documentation notes was not intended to be used for anything but the PR2 robot. Generally speaking, it is known that a transmission is supposed to define how a motor applies effort to a joint or several joints. Therefore, it can be concluded that a transmission must have an association with at least one joint.

Additionally, transmissions mark a point of control for the robot application. If an application wishes to command a robot to move in some manner, then the application must utilize the appropriate interfaces, which in turn triggers one or more robot control primitives which alter the state of the joints. Therefore, a primitive must somehow relate to some transmission and subsequently the parameters provided to the primitive. For example, it could be possible to translate a motor speed to the effort applied at that joint declaratively, and this might require a modification to the previously mentioned control model at the PRIMITIVE component.

With the major components of the model identified via a survey of existing frameworks, what remains is to discover which components are required to produce a full implementation of the RDIS model. To that end, further research is required. At this point, the relationship between the kinematic model and the control model have been established. The specifics of what is contained in the kinematic and control packages is within the scope of this project. The control model is expected to change slightly to provide support for manipulation of the kinematic model during simulation, while the kinematic model will be wholly new to RDIS while the bindings between the control model and the kinematic model will be clearly defined as a contribution to the robotics modeling community.

3.2 Expansion of execution semantics

The ability to generalize device to framework mapping requires documenting the concepts in existing mappings. The domain model captures the invariant features of the device to framework mapping drives the contents of RDIS. In Figure 2, the domain is broken into seven related concepts: connections, state, message semantics, primitives, interfaces, thread control, and robotics domain concepts. CONNECTION refers to the transport used to communicate from the device driver to the framework. Information needed to establish and maintain the connection is defined within this concept. The STATE definition serves two purposes: 1) define constants relevant to other sections and 2) allow for state to be saved and retrieved as part of adhoc and periodic requests. The MESSAGE SEMANTICS refers to the structure of the data which is actually sent to the robot over the connection. This specification is decided by the manufacturer and is generally uniform between primitives. PRIMITIVES focus on describing the firmware interface in order to document the invariant features of the device. The INTERFACE declaration, acting as a logical view of the PRIMITIVES, specifies functions that are available to a developer to control a robot. DOMAIN CONCEPTS map interfaces to domain specific concepts in a framework agnostic manner. These concepts are discussed in detail in [2].

In this research, we expand the basic implementation of each concept to accommodate a larger set of embedded firmware controllers. These tasks include:

1. Addition of a complete kinematic, visual and collision description consistent with existing simulators and frameworks (see Figure 3). The proposed model is designed to accommodate other kinematic chains used for manufacturing and mobile manipulation (discussed in Section 3.1).

2. Standard mechanism for error handling and notification at both the communication and primitive levels. Error handling examples include re-establishment of connection or actions to take based on output parameters. This is particularly relevant to platforms that require a heartbeat request periodically.

3. Expansion of the initial single-threaded implementation to include dual and multi-threading models. A dual model accommodates different input and output threads while a multithreaded model support different frequencies for periodically submitted requests.

4. Refinement of the state concept and how it matches to primitives and interfaces would provide a scripting language for transformation of data. The state variable concept is instrumental in implementing periodic requests asynchronously from the client request/reply system.

5. Management of sensor and actuator error models consistent with existing frameworks will allow for manufacturer provided error models to be propagated to the framework or controller. An example would be a transformation of encoder error to pose error. Although all sources of error (systematic and non-systematic) cannot be accounted for in this approach, it is currently better than existing approaches that abstract out specific device errors.

3.3 Prototyping, Evaluation and Adoption: RDIS-enabled Tools and Frameworks

This challenge focuses on assisting the developer in defining framework drivers that enable the communication with individual devices. We propose a modeling approach where the definitions and mappings are specified independently from the actual framework (*e.g.,* ROS, Player) and robot (*e.g.,* Create, Pioneer). This is achieved by defining RDIS as a DSL rather than using general purpose languages to reduce technical and accidental complexity [24]. Domain-specific modeling [25], and in general model-driven engineering (MDE [26]), is an approach that allows models to be manipulated at the level of abstraction of the application domain the model is intended for, rather than at the level of computing. To bridge the gap between the application domain and the solution domain, MDE uses models to describe complex systems at multiple levels of abstraction and through automated support for transforming and analyzing models. A DSL is defined by means of a *meta-model* that represents the key abstractions and intentions of an expert in a particular domain (in our case frameworks and robotic devices). A meta-model thus specifies the abstract syntax and static semantics of the set of model instances of that language. A model represents an abstraction of the real system, capturing some of its essential properties in order to simulate, and generate code for applications. The manipulation of models is performed through the use of *model transformation*. It transforms a source model into a target model, both conforming to their respective meta-model. Although a model transformation is defined at the meta-model level, it is applied and executed on models.

In order to map the messages exchanges between arbitrary frameworks and robots, RDIS will comprise two meta-models. The first one abstracts the concepts from frameworks. We have already developed a prototype of the models as part of a student project in an advanced graduate course that PI Syriani teaches. The framework meta-model is currently based on reverse-engineering ROS (still in early stages). We plan to perform the same task for the different frameworks to be able to define a framework-independent meta-model. Similarly, we will investigate how this can be performed on the devices side.

Once the meta-models of the language are defined, a rule-based model transformation specify the mapping between them [27]. A rule is a declarative construct that dictates "what" shall be transformed and not "how". It consists of pre-condition and post-condition patterns [28]. The pre-condition pattern determines the applicability of a rule: it is usually described with a left-hand side (LHS) and optional negative application conditions (NACs). The LHS defines the pattern that must be found in the input model to apply the rule. The NAC defines a pattern that shall not be present, inhibiting the application of the rule. The right-hand side (RHS) imposes the post-condition pattern to be found after the rule was applied. An advantage of using the rule-based transformation paradigm is that it allows to specify the transformation as a set of operational rewriting rules instead of using imperative programming languages. Model transformation can thus be specified at a higher level of abstraction (hiding the implementation of the matching algorithms and the modifications of the data structures), closer to the domain of the models the transformation is applied to. Code generators will also be implemented from the RDIS meta-models to each platform in order to deploy the hardware.

The evaluation of RDIS and the developed models will be conducted following these criteria:

- RDIS should be extended to be a model which contains the association between the exposed control interfaces and the behavior which is actuated in simulation.

- RDIS should be general enough to model more than one kinematic category of robot and more than one robot within a category of kinematic design.

- RDIS should be descriptive enough so that the model is rigorously simulatable.

- There should be a mapping between the components and their associations from RDIS to at least one of the major simulation descriptions (Stage, URDF, SDF, and Webots are worthy targets).

- RDIS is concise (not redundant) as measured via model metrics.

- RDIS generated development modules should be sufficiently easy to use as evaluated based on user study and evaluation.

This research will generate a set of artifacts and tools to support the prototyping and evaluation of the domain model and its accompanying language specification. These artifacts encompass three categories: 1) Language definition through language parsers and generators, 2) Framework and language bridge tools and 3) Model metrics and evaluation artifacts. The existing grammar for RDIS will be updated and maintained in a open SVN repository as well as publicized in the CPS Virtual Organization (see Data Management Plan).

4 Curriculum Development Activities

PI Anderson teaches an intelligent robotics course to senior-level undergraduates and first-year graduate students. This course will be augmented to include software engineering in robotics and embedded systems. The prevailing architectures will be presented in terms of their use of standard distributed software engineering paradigms (transparency, cohesion, synchronous vs asynchronous processing, and real-time issues at both the operating system and the applications level), use of standard tool chains to enable reuse and code generation within RDIS and frameworks. Students will learn to evaluate performance in terms of jitter, latency, and maintainability.

PI Syriani teaches an advance course for graduate students on model-based design (CS 691) and, in particular, domain-specific modeling techniques. As part of the course project, some students are currently working on designing a domain-specific language for RDIS in both graphical and textual syntax. The results of this project will serve as a common case-study the student will be working on.

The PIs will continue to work with REU programs targeted at underrepresented groups (DREU, ARTSI, A4RC, etc) to incorporate summer research experiences for students on this project. Undergraduate researchers will be incorporated to assist with coding, testing and documentation while learning important research skills such as reviewing relevant literature, writing and presenting research contributions.

5 Project methodology, management, and dissemination plan

Table 1 outlines the project schedule.

Quarter	Task
Q4 2012	Definition of new kinematic model (joints, links and transmissions); Retrofit to differential drive; Update accompanying RDIS generators and links to frameworks;
Q1 2013	Expand semantics expressiveness (threading, errors, etc) Teach CS 691 on Model-based Design
Q2 2013	Evaluate current iteration of RDIS and tool against target differential drive robotics Identify collaborators that manufacturer sensors, actuators and platforms using differential drive
Q3 2013	Modify model, RDIS and tools to accommodate skid-steer; Teach CS 460/560 Robotics
Q4 2013	Evaluate current iteration of RDIS and tool against target skid-steer
Q1 2014	Modify model, RDIS and tools to accommodate mobile manipulation platforms Teach CS 691 on Model-based Design
Q2 2014	Evaluate current iteration of RDIS and tool against target mobile manipulation platforms Identify collaborators that discover kinematic parameters
Q3 2014	Modify model, RDIS and tools to accommodate bus transports (MLVDS) and RTLinux Summer partnership with NASA; Teach CS 460/560 Robotics
Q4 2014	Evaluate current iteration of RDIS and tool against target platforms running under RTLinux
Q1 2015	Modify model, RDIS and tools to accommodate gantry robots and x-y-z robots Teach CS 691 on Model-based Design
Q2 2015	Evaluate current iteration of RDIS and tool against target manufacturing platforms Identify opportunities for incorporation into manufacturing robot software platforms
Q3 2015	Publish final version RDIS, tools and adapters Teach CS 460/560 Robotics

Table 1: Timeline of proposed tasks.

5.1 Team Member Roles, Responsibilities and Expertise

The success of the proposed research requires both breadth and depth in robotics hardware and software engineering. Dr Anderson's main research area centers on distributed robot systems. However, her twelve years as a software engineer (culminating in a IT Architect position at IBM) has made the shortcomings of existing tools apparent. She designed the circuit board and the software for the eROSI, a novel robot platform [29]. This platform featured an ASCII message-based API available via Bluetooth and images were served wirelessly via UHF channels. These choices directly affected the platform usability for research students such as the undergraduate team at Berea College [30]. In addition, the PI has either programmed or modified drivers or firmware for robots and devices including the Koala, Finch, Create, Ar.Drone, Lego Mindstorms, Calliope (Dynamixel-based 4 DOF arm), Handyboard, GPS modules, lasers, analog and digital IR and ultrasonic sensors, and custom boards using ATMega chip and serial Bluetooth ICs to interface with Player/Stage, Alice/PREOP, ROS, Carmen, Webots and custom firmware applications. In addition, the PI has studied open source implementations of other drivers and frameworks including PSOS (Pioneer robots), Tekkotsu, and LCM. She was the organizer of the 2010 AAAI Robotics Workshop titled "Enabling Intelligence through Middleware" an effort to increase awareness of tools within the community and tool needs outside the community [31].

The engineering of modeling language and transformation is contingent to the success of the project. Co-PI Syriani's expertise in model-based design is thus critical to the project. He is the author of the T-Core [32] and MoTif [33] transformation languages. In addition, the Co-PI has ample experience with existing modeling and transformation languages based on the Eclipse Modeling Framework (EMF). The PIs are therefore in a unique position given their expertise, experience and enthusiasm to affect accessibility of robotics controller development within the larger community.

5.2 Dissemination Plan

Broad dissemination plans include both the academic and industrial communities. Traditional academic dissemination plans include publications and conference presentations in both the educational and robotics software engineering communities. In addition, a bridge to the CPS community will be created via the CPS Virtual Organization (CPS-VO) by publicizing results results and collaboration opportunities. Future plans include workshops at conference venues as well as at partner campuses will provide hands-on opportunities for those that wish to use the tool for teaching or design. A website will be maintained and all software will be open source. However, primary means of dissemination will utilize partnerships with manufacturers or tool developers as we have seen this method is effective at making other artifacts widely available.

Additional kinematic designs are motivated by partnerships with NASA and RTP. NASA is migrating a robotic platform from VxWorks to Ubuntu with a future update to include RTLinux. This custom kinematic chain involves manipulators with haptic sensors on a MLVDS bus (a new transport). RTP (Huntsville Research Technology Park) is an initiative by the governor of Alabama to create a National Robotics Technology Development and Training Center at Calhoun Community College. Many robot platforms have been purchased and donated for training and are available for evaluation as candidate platforms for RDIS inclusion. Both opportunities expand the platforms that can modeled and contribute to the domain model that can be generalized across other platforms.

5.3 Methodology and Timeline

The research approach consists of iterative design and integrated usability checks. Rather than attempt to create the research tools in a single iteration, it is better to start with a core of features and iteratively add to those features. This approach allows for the usability testing within the first 12 months as an input into the next iteration. The schedule details the work for two graduate students for the three years: one student to focus on analysis of platforms and the evolution of RDIS and one student to focus on the graphical tool for building and incorporating the RDIS into tools and frameworks. Undergraduate students will assist with coding, testing and support activities. The project team will meet weekly to discuss progress on features and use cases and any design issues. Ongoing activities include dissemination through web sites, conferences and site visits. Target tools and languages include Eclipse, C, C++ and Python. Target frameworks include ROS, Player/Stage, PREOP and URBI as license allows. Target differential drive platforms include Pioneer, Koala, ER-1, custom based on android platform and RC-car base (skid-steer). Other kinematic chains will include the Calliope and Chaira, two mobile manipulation platforms created at CMU. Additional platforms will be evaluated based on partnerships with manufacturers and industrial labs.

6 Intellectual Merit

RDIS provides a mechanism for centralizing the knowledge of the syntax (how to access the service) and semantics (what is the meaning of the input/output of the service) to the embedded system itself through a fully descriptive, declarative language. To accomplish this, we propose an iterative approach that builds a domain model that will be modified to support an increasing larger set of popular sensors and kinematic designs. This domain model will drive the evolution of the RDIS and accompanying toolsets to greatly improve the ability of developers and researchers to incorporate new platforms and sensors in a wider range of frameworks. This aspect of the proposed project is transformative; it could potentially affect the creation of new hardware platforms, reduce the complexity of device drivers (encourage new devices) and lower the learning curve to working with platforms.

Although there are many benefits to utilizing the RDIS outside of the hardware the ultimate goal is best met by embedding the robot device descriptions within the device. Discovery occurs when the design environment queries the device for its supported services or API. The initial approach for platforms that support onboard reconfigurable firmware is to augment the firmware to support a single command that communicates the RDIS. The information provided by the RDIS can be used by any RDIS-enabled development environment. It is expected that manufacturers will choose RDIS to enable their devices once there are more RDIS-enabled environments available. The Finch designer has already agreed to update the firmware of a couple of select models and has committed to including the command once it is more stable and is being adopted. In the "Sketching in Hardware" community, many of the robotic devices are custom built by connecting actuators and sensors to netbooks or single board computers (SBCs). Although RDIS cannot completely specify all possible interactions with every sensor and actuator, the communication to the computer and to the peripheral connection mechanisms can be queried and described.

Reconfigurable hardware provides a unique challenge. Rather than a static description, RDIS becomes a mechanism for communicating changes. As a longer-term goal, research methods that learn the current configuration based on embedded sensors could be appropriately applied here. Either building blocks or configurable linkages would embed proprioceptive sensors to establish kinematic parameters needed for programming. This kinematic learning can also be accomplished by augmenting existing systems with small standalone, networked sensors that are placed at joints. Although initial iterations will focus on static hardware designs, the application to reconfigurable robots could enable “on-the-fly” physical reconfiguration with reasonable ability to program new capabilities in the field.

7 Broader Impact

The broader impacts of the proposed work can be categorized as either enabling more efficient controller design or enabling new research. RDIS existence for a given platform will make available a wider range RDIS-enabled frameworks and tools. Integrated development environments such as Eclipse will be augmented with plug-ins that read the RDIS (from the device or from an online repository) that will present the developer with visual representations of the services and will allow for software creation through component composition for those not interested in using frameworks. Developers of custom environments can create an RDIS and will have access to standardized tools without needing to write device specific plugins for easy framework.

The proposed work also enables new research. The RDIS will change the components in robotics kits so that they can be reconfigured. This requires additional research in kinematic discovery with low cost components [34]. New instruments for measuring self-efficacy in robotics skills will enable the validation of new tools and techniques in robotics tool development. Automatic component discovery can be leveraged in other domains where the interfaces are fairly static and there are many data providers and many candidate algorithms. This research enables a new model of reuse within the research community that could advance validation of published results through sharing of software artifacts.

Additional broader impacts relate directly to the activities of the PI. The PI serves as an active mentor within her university and research community. She advises senior project groups in computer science and electrical engineering. As a PI in the ARTSI alliance (Advancing Robotics Technology for Societal Impact), she has fostered productive relationships with HBCUs (historically black colleges and universities) that have resulted in talks, workshops, sharing of technical expertise and REU student placement (seven students to date). Other REUs have been hosted from the Software Engineering REU site at UA and the DREU program. All REUs/undergraduate/graduate advisees receive active mentoring including introductions to graduate faculty at other schools where appropriate, review of application materials, recommendation letters, job reference letters and publication, speaking and attendance opportunities at conferences such as Grace Hopper, Richard Tapia, IJCAI, AAAI, ICRA and IROS.

This project will integrate research and education in a number of ways. First, the PIs will engage graduate students at UA to support the project. Through their sustained interaction with the PIs, these new researchers will gain expertise in several aspects of robotics and software engineering, including model-driven engineering. Thus, one result of this project will be a group of highly trained and qualified researchers who will be capable of sustaining individual research programs in software engineering. Second, the PIs will integrate the research results from this project into their numerous graduate and upper-level undergraduate courses courses at UA. When hiring graduate research assistants (GRAs) for this project, we will recruit and encourage persons from underrepresented groups to apply. PI Anderson and Co-PI Syriani have previous success recruiting and mentoring students from underrepresented groups. Part of this success is due to the unique status of The University of Alabama among flagship universities as a major recruiter of both minority faculty, administrators, and students (Top 5).

8 Results from Prior NSF Support

1. Monica Anderson - PI for the NSF Grant: CCLI: Enhancing student motivation in the first year computing science curriculum (DUE- 0736789), 04/01/2008-08/31/2011. This is an ongoing project that addresses retention issues due to motivation through specially designed modules that use PREOP in a CS0 or CS1 laboratory setting. We provided PREOP workshops to teachers at the ARTSI Faculty Meeting, demonstrated PREOP at the Google education summit and added PREOP to Alice instructor training (July 2011). Three papers have been published including two conference papers and two journal papers [35, 36, 37, 23].

2. Monica Anderson - PI for the Grant: ARTSI-Advancing Robotic Technology for Societal Impact (BPC-A- 0742123), 09/01/07-12/31/2012. This is an ongoing broadening participation grant that increases the number of students interested in computer science and robotics through both research and creative experiences. Robotics programs have been established or enhanced at 14 HBCUs. The PI has provided each school with both onsite and remote instructional support ranging from hands-on workshops on open-source robotics development environments and controller development to hardware assembly instructions. Seven summer research assistants have been hosted at UA, with one student contributing to an accepted paper [22] and resulting in numerous poster presentations.

3. Monica Anderson - PI for the Grant: SGER: Impact of Intermittent Networks on Team-based Coverage (IIS-0846976), 09/01/2008-08/31/2009. This project investigated both surveillance in constrained environments using limited resources and methods for coordinating robot teams with limited communications capability. The novel approach of using ALUL and a QOS metric allowed for balanced target acquisition and tracking [38, 39, 40, 41].

4. Monica Anderson - Co-PI for the Grant: EMT: Collaborative Research: Primate-inspired Heterogeneous Mobile and Static Sensor Networks (CNS: 0829827) 09/01/2008-08/31/2011. This project investigates bio-inspired approaches for multirobot coordination. We show that given a greedy approach to selecting the next point to search, observation information provides more relevant input to the next action selected. Experimental results show that using observation to infer state and intent to disperse nodes performs better than non-communicative and potential field based cooperation and in some cases direct communications. [42, 43, 44, 45, 46].

5. Monica Anderson - PI for the Grant: University of Alabama Participation of EPSCOR Institution in SSR-RC: QOS service metrics for unmanned surveillance (IIP: 1026528). 06/15/2010-06/14/2012. We consider ALUL as a metric that indicates the target acquisition ability of a particular system configuration. When used in conjunction with temporal constraints, we can intelligently automate camera coverage to improve target acquisition and tracking performance of the system. The results from the experiments confirm that the coverage in constrained environments when the existing camera configuration cannot view large portions of the region of our interest improves when ALUL is considered. To date, one conference paper and one journal article have been accepted [47, 48].

6. Eugene Syriani - New investigator and has no prior NSF support.