An Industrial Robotic Knowledge Representation for Kit Building Applications

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Abstract— **The IEEE RAS Ontologies for Robotics and Automation Working Group is dedicated to developing a methodology for knowledge representation and reasoning in robotics and automation. As part of this working group, the Industrial Robots sub-group is tasked with studying industrial applications of the ontology. One of the first areas of interest for this subgroup is the area of kit building or kitting which is a process that brings parts together in a kit and then moves the kit to the assembly area where the parts are used in the final assembly. Kitting itself may be viewed as a specialization of the general bin-picking problem. This paper examines the knowledge representations that have been developed for the kitting problem and presents our implementation of the knowledge representations.**

I. INTRODUCTION

Kitting is the process in which several different, but related items are placed into a container and supplied together as a single unit. In industrial assembly of manufactured products, kitting is often performed prior to final assembly. Manufacturers utilize kitting due to its ability to provide cost savings [3] including saving manufacturing or assembly space [13], reducing assembly workers walking and searching times [15], and increasing line flexibility [2] and balance [10].

Several different techniques are used to create kits. A kitting operation where a kit box is stationary until filled at a single kitting workstation is referred to as *batch kitting*. In *zone kitting*, the kit moves while being filled and will pass through one or more zones before it is completed. This paper focuses on batch kitting processes.

In batch kitting, the kit's component parts may be staged in containers positioned in the workstation or may arrive on a conveyor. Component parts may be fixtured, for example placed in compartments on trays, or may be in random orientations, for example placed in a large bin. In addition to the kit's component parts, the workstation usually contains a storage area for empty kit boxes as well as completed kits.

Kitting has not yet been automated in many industries where automation may be feasible. Consequently, the cost of building kits is higher than it could be. We are addressing this problem by building models of the knowledge that will be required to operate an automated kitting workstation in an agile manufacturing environment. This workstation must be able to cope with variations in kit contents, kit layout, and component supply. We also plan to develop a simulated kitting workstation for model validation. Our models include representations for non-executable information about the workstation such as information about a robot, parts, kit designs, end effectors, etc., models of executable information such as actions, preconditions, and effects, and models of the process plan necessary for kit construction. A discussion of the functional requirements for the process plan may be found in [1]. For our automated kitting workstation, we assume that a robot performs a series of pick-and-place operations in order to construct the kit. These operations include:

1) Pick empty kit and place on work table.
2) Pick multiple component parts and place in kit.
3) Pick completed kit and place in full kit storage area.

Each of these actions may be a compound action that includes other actions such as end-of-arm tool changes, path planning, and obstacle avoidance.

It should be noted that multiple kits may be built simultaneously. Finished kits are moved to the assembly floor where components are picked from the kit for use in the assembly procedure. The kits are normally designed to facilitate component picking in the correct sequence for assembly. Component orientation may be constrained by the kit design in order to ease the pick-to-assembly process. Empty kits are returned to the kit building area for reuse.

Although the knowledge requirements described in the

previous paragraph have been identified for the kitting domain, they are clearly applicable to many types of industrial robot applications (and likely to robot applications in other fields). As such, we expect that these knowledge requirements will serve as the basis for the industrial robot ontology being developed in the IEEE RAS Ontologies for Robotics and Automation Working Group [11] (henceforth referred to as the IEEE WG). Throughout the process of developing the kitting ontology, the group will constantly look at the applicability of the requirements outside of kitting and move the pertinent knowledge "up" the ontology (whether in the portion that models the kitting sub-domain, the industrial robot domain, or the upper ontology), as appropriate.

In keeping with our philosophy of producing standards in conjunction with the IEEE WG, we wish the models being developed by this effort to be as widely applicable as possible. To support this desire, we have created a layered model abstraction where users may adopt as many or few of the layers of the abstraction as make sense for their specific application. The architecture shown in Figure 1, though developed for the implementation of the kitting ontology, can be equally applicable to the implementation of any type of formal manufacturing knowledge representation. Said in a different way, the implementor can plug in a knowledge representation for a different domain and the architecture would still be valid. In a similar manner, different planning language abstractions could be utilized in the planning language layer of the abstraction and different planning/execution systems could be utilized in the robot language layer of the abstraction.

Specifics on the overall architecture may be found in Section II. An example of the various knowledge representations and the flow from one to the next is presented in Section III. Finally, conclusions and future work may be found in Section IV.

II. ARCHITECTURE DESCRIPTION

The main focus of this work is on the development of knowledge models that allow a kitting workstation to construct kits in an agile manufacturing environment. However, in order to validate these knowledge models, we felt that it was important to be able to utilize the models to construct kit building plans, and then to execute these plans in dynamic virtual and real environments. Due to the advent of open source robotic operating systems such as ROS[1][6] and simulation packages such as USARSim [4] we do not need to design these systems ourselves. However, our architecture must be designed to represent the required knowledge base in several different abstractions that are likely to be required by these systems as the knowledge flows from domain and process specification, to plan generation, to plan execution. As shown in Figure 1, the abstraction is decomposed into four distinct layers of *Domain Specific Information*,
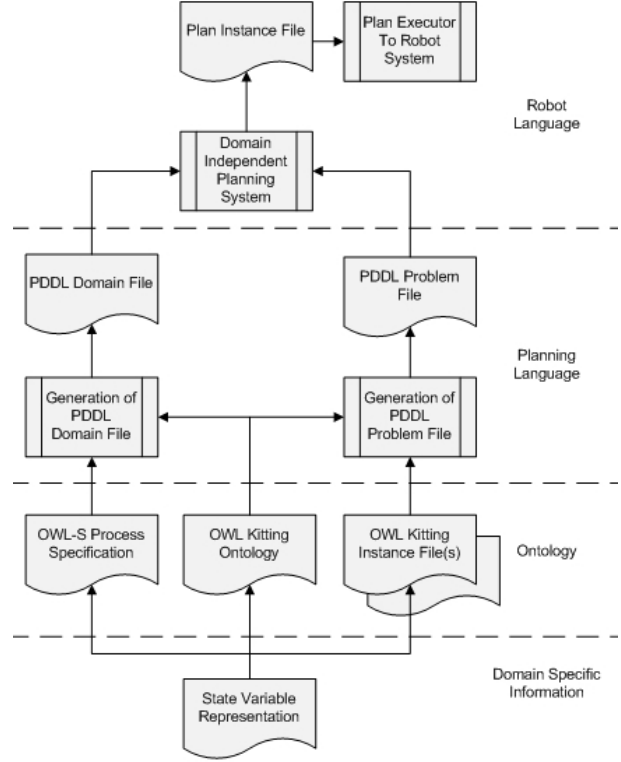
Fig. 1.   Kitting data flow abstraction.

Ontology, *Planning Language*, and *Robot Language* that correspond to these knowledge requirements. In this paper, we will discuss the layers of the Domain Specific Information through Planning Language. Implementors of the abstraction are free to connect to the knowledge interface at the layer that makes sense for their particular application. For our simulated kitting workstation, we intend to fully design the Domain Specific Information and the Ontology and then utilize open source tools that will automatically generate the remaining layers and provide a workstation simulation.

A. Domain Specific Information

The foundation for the knowledge representation is domain specific information that is produced by an expert in the particular field of study. This includes information on items ranging from what actions and attributes are relevant, to what are the necessary conditions for an action to occur and what are the likely results of that action. We have chosen to encode this basic information in a formalism know as a state variable representation (SVR) [14]. This information will then flow up the abstraction and be transformed into the ontology, planning language, and robot language. In a SVR, each state is represented by a tuple of values of n state variables $\{x_1, \ldots, x_n\}$, and each action is represented by a partial function that maps this tuple into some other tuple of values of the n state variables.

To build the SVR, the group has taken a very systematic approach of identifying and modeling the concepts. Because the industrial robot field is so broad, the group decided

to limit its efforts to a single type of operation, namely kitting. A scenario was developed that described, in detail, the types of operations that would be performed in kitting, the sequencing of steps, the parts and machines that were needed, constraints on the process such as pre- and post-conditions, etc. For this scenario, a set of concepts were extracted and defined. These concepts served as the initial requirements for the kitting SVR. The concepts were then modeling in our SVR, building off of the definitions and relationships that were identified in the scenario.

A SVR relies on the elements of constant variable symbols, object variable symbols, state variable symbols, rigid relations, and planning operators. These are defined for the kitting domain in the rest of this section.

1) Constant Variable Symbols: For the kitting domain, there is a finite set of constant variable symbols that must be represented in the system. In the SVR, constant variable symbols are partitioned into disjoint classes corresponding to the objects of the domain. The finite set of all constant variable symbols in the kitting domain is partitioned into the following sets:

- A set of *Parts* $\{part_1, part_2, \ldots\}$: *Parts* are the basic items that will be used to fill a kit.
- A set of *PartTrays* $\{pt_1, pt_2, \ldots\}$: *Parts* arrive at the workstation in *PartTrays*. Each part is at a known position in the *PartTray*. Each *PartTray* contains one type of *Part*.
- A set of *KitTrays* $\{kt_1, kt_2, \ldots\}$: A *KitTray* can hold *Parts* in known positions.
- A set of *KitInstances* $\{kins_1, kins_2, \ldots\}$: A *KitInstance* is built when *Parts* are placed in a *KitTray*. A *KitInstance* consists of a *KitTray* and, possibly, some *Parts*. A *KitInstance* is empty when it does not contain any *Part* and finished when it contains all the *Parts* that constitute a kit.
- A symbol *WorkTable* – $wtable$: A *WorkTable* is an area in the kitting workstation where *KitTrays* are placed to build *KitInstances*.
- A set of *LargeBoxWithKits* $\{lbwk_1, lbwk_2, \ldots\}$: A *LargeBoxWithKits* contains only finished *KitInstances*.
- A set of *LargeBoxWithEmptyKitTrays* $\{lbwekt_1, lbwekt_2, \ldots\}$: A *LargeBoxWithEmptyKitTrays* is a box that contains only empty *KitTrays*.
- A set of *Robots* $\{r_1, r_2, \ldots\}$: A *Robot* in the kitting workstation is a robotic arm that can move objects in order to build *KitInstances*.
- A set of *EndEffectors* $\{eff_1, eff_2, \ldots\}$: *EndEffectors* are used in a kitting workstation to manipulate *Parts*, *PartTrays*, *KitTrays*, and *KitInstances*. An *EndEffector* is attached to a *Robot*.
- A set of *EndEffectorHolders* $\{effh_1, effh_2, \ldots\}$: An *EndEffectorHolder* is a storage unit that holds one type of *EndEffector*.
- A symbol *EndEffectorChangingStation* – $chstation$: An *EndEffectorChangingStation* is made up of *EndEffectorHolders*.

2) Object Variable Symbols: Object variable symbols are typed variables which range over a class or the union of classes of constant variable symbols. Examples of object variable symbols are $r \in Robots$, $kt \in KitTrays$, etc.

3) State Variable Symbols: A state variable symbol is defined as follows: $x : A_1 \times \ldots \times A_i \times S \rightarrow B_1 \cup \ldots \cup B_j$ $(i, j \geq 1)$ is a function from the set of states (S) and at least one set of constant variable symbols $A_1 \times \ldots \times A_i$ into a set of constant variable symbols $B_1 \cup \ldots \cup B_j$.

The use of state variable symbols reduces the possibility of inconsistent states and generates a smaller state space. The following state variable symbols are used in the kitting domain:

- effloc: *EndEffectors*$\times$S $\rightarrow$*Robots* $\cup$ *EndEffectorHolders*: designates the location of an *EndEffector* in the workstation, i.e., in a *EndEffectorHolder* or attached to a *Robot*.
- reff: *Robots*$\times$S $\rightarrow$*EndEffectors* $\cup$ $\{nil\}$: designates the *EndEffector* attached to a *Robot* if there is one attached, otherwise *nil*.
- onworktable: *WorkTable*$\times$S $\rightarrow$*KitInstances* $\cup$ *KitTrays* $\cup$ $\{nil\}$: designates the object placed on the *WorkTable*, i.e., a *KitInstance*, a *KitTray*, or nothing (*nil*).
- kinsloc: *KitInstances*$\times$S $\rightarrow$*LargeBoxWithKits* $\cup$ *WorkTable* $\cup$ *Robots*: designates the different possible locations of a *KitInstance* in the workstation, i.e., in a *LargeBoxWithKits*, on the *WorkTable*, or being held by a *Robot*.
- ktloc: *KitTrays*$\times$S $\rightarrow$*LargeBoxWithEmptyKitTrays* $\cup$ *Robots* $\cup$ *WorkTable*: designates the different possible locations of a *KitTray* in the workstation, i.e., in a *LargeBoxWithEmptyKitTrays*, on a *WorkTable* or being held by a *Robot*.
- partloc: *Parts*$\times$S $\rightarrow$*PartTrays* $\cup$ *KitInstances* $\cup$ *Robots*: designates the different possible locations of a *Part* in the workstation, i.e., in a *PartTray*, in a *KitInstance*, or being held by a *Robot*.
- rhold: *Robots*$\times$S $\rightarrow$*KitTrays* $\cup$ *KitInstances* $\cup$ *Parts* $\cup$ $\{nil\}$: designates the object being held by a *Robot*, i.e., a *KitTray*, a *KitInstance*, *Part*, or nothing (*nil*). It is assumed that the *Robot* is already equipped with the appropriate *EndEffector*.
- islbwkfull: *LargeBoxWithKits*$\times$S $\rightarrow$ $\{0\}$ $\cup$ $\{1\}$: designates if a *LargeBoxWithKits* is full (1) or not (0).
- islbwektempty: *LargeBoxWithEmptyKitTrays*$\times$S $\rightarrow$ $\{0\}$ $\cup$ $\{1\}$: designates if a *LargeBoxWithEmptyKitTrays* is empty (1) or not (0).
- isptempty: *PartTrays*$\times$S $\rightarrow$ $\{0\}$ $\cup$ $\{1\}$: designates if a *PartTray* is empty (1) or not (0).
- efftype: *EndEffectors*$\times$S $\rightarrow$*KitTrays* $\cup$ *KitInstancess* $\cup$ *Parts*: designates the type of object an *EndEffector* can hold, i.e., *KitTrays*, *KitInstances*, or *Parts*.
- effhtype: *EndEffectorHolders*$\times$S $\rightarrow$*EndEffectors*: designates the *EndEffector* that an *EndEffectorHolder* can hold.

4) Rigid Relations: efftype and effhtype are rigid relations since their values do not vary from one state to another.

In each state, a given *EndEffector* will always hold the same type of object and a given *EndEffectorHolder* will always hold the same *EndEffectors*.

5) Planning Operators and Actions: A planning operator is used to describe one of the procedures that can be used to move from one state to another. Our kitting domain is composed of eight operators. Only the operators' names and descriptions are mentioned in this section. Section III provides a complete description of a planning operator through an example.

1) *take-kt*(r,kt,$lbwekt$,eff): The *Robot* r equipped with the *EndEffector* $eeff$ picks up the *KitTray* kt from the *LargeBoxWithEmptyKitTrays* $lbwekt$.
2) *put-kt*(r,kt,$wtable$): The *Robot* r puts down the *KitTray* kt on the *WorkTable* $wtable$.
3) *take-kins*(r,$kins$,$wtable$,eff): The *Robot* r equipped with the *EndEffector* eff picks up the *KitInstance* $kins$ from the *WorkTable* $wtable$.
4) *put-kins*(r,$kins$,$lbwk$): The *Robot* r puts down the *KitInstance* $kins$ in the *LargeBoxWithKits* $lbwk$.
5) *take-p*(r,$part$,pt,eff): The *Robot* r uses the *EndEffector* eff to pick up the *Part* $part$ from the *PartTray* pt.
6) *put-p*(r,$part$,$kins$): The *Robot* r puts down the *Part* $part$ in the *KitInstance* $kins$.
7) *attach-eff*(r,eff,$effh$): The *Robot* r attaches the *EndEffector* eff, situated in the *EndEffectorHolder* $effh$.
8) *remove-eff*(r,eff,$effh$): The *Robot* r removes the *EndEffector* eff and puts it in the *EndEffectorHolder* $effh$.

An action *a* can be obtained by substituting the object variable symbols that appear anywhere in the operator with constant variable symbols. For instance, the operator *take-p*(r,$part$,pt,eff) in the kitting domain can be translated into the action *take-p*(r_1,$part_1$,pt_1,eff_2) where r_1, $part_1$, pt_1, and eff_2 are constant variable symbols in the classes *Robots*, *Parts*, *PartTrays*, and *EndEffectors*, respectively.

B. Ontology

"Ontology deals with questions concerning what entities exist or can be said to exist, and how such entities can be grouped, related within a hierarchy, and subdivided according to similarities and differences" [18].

Knowledge models may take many forms ranging from informal natural language, to XML schemas, to ontologies. For the development of the knowledge representation, the industrial robots sub-group has decided to use the Web Ontology Language (OWL) [17] as the knowledge representation language. OWL is a family of knowledge representation languages for authoring ontologies and is endorsed by the World Wide Web Consortium (W3C). It is characterized by formal semantics and Resource Description Framework/eXtensible Markup Language (RDF/XML)-based serialization for the Semantic Web. OWL was chosen by the group because of its popularity among the ontology development community, its endorsement by the W3C, as well as the number of tools and reasoning engines that are available. OWL was also selected

as the representation language that will be used in the overall IEEE WG efforts.

In addition to OWL, the industrial robots subgroup will also be using OWL-S [12] to represent the processes and actions that the robot will perform. OWL-S is an ontology built on top of OWL by the DARPA Agent Markup Language (DAML) program [5] for describing Semantic Web Services. Many of the constructs that are used to describe services are equally applicable to encoding our SVR. For example, concepts such as preconditions, results, inputs, outputs, effects, and participants are generic enough to be applied to just about any type of process specification.

Since this work is being directed at the IEEE RAS Ontologies for Robotics and Automation Working Group, it is appropriate that our domain specific knowledge be encoded in an OWL ontology at the first domain independent layer of our abstraction. The knowledge contained in this layer is derived from our SVR and may also contain information that has been collected over other domains. The knowledge is sufficient for a planning system to understand the specific problem domain and construct a plan for creating the desired kit from the given resources.

As more detailed scenarios are determined and a richer set of concepts are uncovered, the ontology will be partitioned based upon the generality of the concept, with the most generally applicable concepts being "higher" in the ontology so they are available to other domains and the more detailed concepts being "lower" in the ontology because they will likely be very specific to the kitting area. An example of a general concept may be a Robot while a specific concept may be a KitTray.

As shown in Figure 1, the information in our ontology is divided into three sets of files and consists of a representation of the process specification, the kitting ontology, and the instance file. The process specification file is based off of the planning operators from the SVR and contains descriptions of the individual actions and sequences necessary to construct a kit, e.g. gripping a component from a tray. The kitting ontology file is based off of the constant variable symbols and state variable symbols and contains the concepts related to the specific items that compose the kitting domain, e.g. the hierarchy of what it means to be a $part_A$. That a $part_A$ is a type of *Part*, and that all *Parts* contain properties such as the part's weight, dimensions, and grip points. The instance file is based off of the SVR object variable symbols and contains specific information on *this* particular kitting problem and configuration, e.g. *KitTray* kt_1 contains four *Parts* of type $part_A$.

While this file set provides a complete description of the problem domain and environment, most planning systems cannot directly ingest information from an ontology. Therefore, the next layer of the data abstraction known as the Planning Language layer was created.

C. Planning Language

The Planning Domain Definition Language (PDDL) [8] is an attempt by the domain independent planning community

to formulate a standard language for planning. A community of planning researchers has been producing planning systems that comply with this formalism since the first International Planning Competition held in 1998. This competition series continues today, with the seventh competition being held in 2011. PDDL is constantly adding extensions to the base language in order to represent more expressive problem domains. Our work is based on PDDL Version 3.

By placing our knowledge in a PDDL representation, we enable the use of an entire family of open source planning systems. As shown in Figure 1, each PDDL file-set consists of two files that specify the domain and the problem. The PDDL domain file is composed of four sections that include requirements, types and constants, predicates, and actions. This file may be automatically generated from a combination of information that is contained in the OWL-S process specification file and the OWL Kitting Ontology file.

The requirements section specifies which extensions this problem domain relies on. The planning system can examine this statement to determine if it is capable of solving problems in this domain. In PDDL, all variables that are used in the domain must be typed. Types are defined in the types section. It is also possible to have constants that specify that all problems will share this single value. For example, in the simplest kitting workstation we will have a single Robot r_1. Predicates specify relationships between instances. For example, an instance of a *KitTray*, kt_1, can have a physical location and contains instances of *Parts*, $part_A$, $part_B$, and $part_C$. The final section of the PDDL domain file is concerned with actions. An action statement specifies a way that a planner affects the state of the world. The statement includes parameters, preconditions, and effects. The preconditions dictate items that must be initially true for the action to be legal. The effect equation dictates the changes in the world that will occur due to the execution of the action.

The second file of the PDDL file-set is a problem file. The problem file specifies information about the specific instance of the given problem. This file contains the initial conditions and definition of the world (in the init section) and the final state that the world must be brought to (in the goal section). A specific example of the ontology to planning language conversion is provided in Section III.

III. EXAMPLE OF OPERATION

The purpose of this section is to illustrate the various knowledge representations, depicted in Figure 1, and the flow from one knowledge representation to the next through a specific example.

A. State Variable Representation

In the example, the *Robot* has to build a kit that contains two *Parts* of type A, one *Part* of type B and one *Part* of type C. The kitting process is completed once the kit is placed in the *LargeBoxWithKits*. Section III-B details the steps that build the PDDL domain file while Section III-C discusses the process that builds the PDDL problem file.

The state variable representation defines the necessary parameters for the PDDL domain and problem files. The PDDL domain file contains predicates, characterized by state variable symbols, and actions. The PDDL problem file contains the objects present in the problem instance, characterized by constant variable symbols, the initial state s_0 description and the goal s_G.

a) Constant Variable Symbols: The kitting domain proposed for the example contains a *Robot* r_1, a *KitTray* kt_1, a *LargeBoxWithEmptyKitTrays* $lbwekt_1$, a *LargeBoxWithKits* $lbwk_1$, a *WorkTable* $wtable$, three *PartTrays* pt_A, pt_B, and pt_C, *Parts* $part_{A-1}$, $part_{A-2}$, $part_B$, and $part_C$, two *End-Effectors* eff_1 and eff_2, and two *EndEffectorHolders* $effh_1$ and $effh_2$. Since a *KitInstance* is by definition a *KitTray* that contains *Parts*, the kitting domain also contains a constant variable symbol $kins_1$ from *KitInstance*.

b) State Variable Symbols: The state variable symbols for the kitting domains are the ones defined in section II-A.3.

c) Rigid Relations: As stated in section II-A.4, the kitting domain has two rigid relations: efftype and effhtype that can be stated as follows: efftype(eff_1)={$part_{A-1}$,$part_{A-2}$,$part_B$,$part_C$} and efftype(eff_2)={kt_1,$kins_1$}. In the same way, effhtype can be stated as follows: effhtype($effh_1$)={eff_1} and effhtype($effh_2$)={eff_2}.

d) Initial State: The initial state s_0 can be represented by the following set of state variable symbols:
s_0={rhold(r_1)=nil, effloc(eff_1)=$effh_1$, effloc(eff_2)=$effh_2$, isptempty(pt_A)=0, isptempty(pt_B)=0, isptempty(pt_C)=0, onworktable($wtable$)=nil, islbwektempty($lbwekt_1$)=0, islbwkfull($lbwk_1$)=0, partloc($part_{A-1}$)=pt_A, partloc($part_{A-2}$)=pt_A, partloc($part_B$)=pt_B, partloc($part_C$)=pt_C, ktloc(kt_1)=$lbwekt_1$}.

e) Goal State: The goal state s_G can be represented by the following set of state variable symbols:
s_g ={partloc($part_C$)=$kins_1$, partloc($part_B$)=$kins_1$, partloc($part_{A-2}$)=$kins_1$, partloc($part_{A-1}$)=$kins_1$, kinsloc($kins_1$)=$lbwk_1$}.

f) Action: Among the eight planning operators introduced in Section II-A.5, only the planning operator *take-kt(r,kt,$lbwekt$,eff)* will be discussed in this example. By substituting the object variable symbols described in the definition of the planning operator *take-kt* with the constant variable symbols defined in this example, the following action is produced:

- *take-kt(r_1,kt_1,$lbwekt_1$,eff_2)*: The *Robot* r_1 equipped with the *EndEffector* eff_2 picks up the *KitTray* kt_1 from the *LargeBoxWithEmptyKitTrays* $lbwekt_1$.
  - precond: ktloc(kt_1)=$lbwekt_1$, rhold(r_1)=nil, reff(r_1)=eff_2, effloc(eff_1)=r_1, islbwektempty($lbwekt_1$)=0
  - effects: ktloc(kt_1)←r_1, rhold(r_1)←kt_1

B. Process for the PDDL Domain File

Once the state variable representation is defined, an OWL-S process specification and OWL ontology is built. This must be constructed by hand from the information in the SVR

as described in Section II-B. For this example, the specific action *take-kt*'s encoding into OWL-S will be discussed.

1) OWL-S Representation: Once the action is specified in the SVR, we can use that information to create an OWL-S process. We are modeling the action as a process and including information about its data inputs and outputs, the preconditions that have to be true for it to be performed, and the result that will be true after the process is executed. In our example, the process is an atomic process because it only involves a single interaction and consists of only one step. If it were a more complex process that involved multiple sub-actions, it would be modeled by an OWL-S composite process.

In the SVR, the preconditions clearly map to the OWL-S precondition. These can be represented in languages such as KIF [7] (Knowledge Interchange Format), SPARQL [16] (SPARQL Protocol and RDF Query Language), or SWRL [9] (Semantic Web Rule Language). The rules point to classes and instances in the ontology that model the concepts of kit tray (kt), a set of large box with empty kit trays ($lbwekt$), a robot (r), and a robot end effector (eff). The SVR effects map to the OWL-S results and are also represented in one of the rules languages above. In the case of the *take-kt* action, the result would specify that the location of the kit tray is no longer in a fixed location and is now in the robot end effector.

Though not explicitly represented in the SVR, data inputs and outputs are an important part of the OWL-S representation and can be inferred from the SVR. Specifically, it needs to know which robot is performing the action (r_1), which kit tray needs to be picked up (kt_1), which end effector is on the robot (eff_2), and from which box the robot needs to pick up the kit tray ($lbwekt_1$). The output of this action would be a Boolean stating whether the action was completed successfully or not.

2) PDDL Domain File: An external tool is used to generate the PDDL Domain File from the OWL/OWL-S representation. Due to space constraints, only an excerpt of the PDDL domain file is displayed in Figure 2.

```
(define (domain kitting-domain)
 (:requirements :strips :typing)
 (:types part parttray kittray kitinstance worktable
  largeboxwithkits largeboxwithemptykittrays robot
  endeffector ...)
 (:predicates
  (effloc ?eff - endeffector ?r - robot
   ?effh - endeffectorholder)
  (efftype ?effh - endeffectorholder ?eff - endeffector)
  ...
 )
 (:action take-kt
  :parameters (?r - robot ?kt - kittray
   ?lbwekt - largeboxwithemptykittrays
   ?eff - endeffector)
  :precondition (and (rhold ?robot ?nil)
     (ktloc ?kittray ?largeboxwithemptykittrays)
     (reff ?robot ?endeffector)
     (effloc ?kittray ?robot)
     (not (islbwektempty (?largeboxwithemptykittrays))))
  :effect (and (ktloc ?kittray ?robot)
         (rhold ?robot ?kittray))
 )
```

Fig. 2. Excerpt of the PDDL domain file for kitting.

C. Process for the PDDL Problem File

The PDDL problem file is generated by a chain of data conversions that take the SVR through an OWL representation to the PDDL representation.

1) OWL Representation: The OWL instance files shown in Figure 1 are derived from the SVR initial and goal states (s_0, s_G). These files contain specific instances of the classes that have been previously defined in the OWL ontology. Two specific instance files are required for the representation with both files containing the same class structures. The difference between the two is that in the *InitFile* the specific properties of the instantiated classes represent the initial state of the domain, and in the *GoalFile* the specific properties of the instantiated classes represent the goal state of the domain.

2) PDDL Problem File: The PDDL file is once again automatically generated. An excerpt of the PDDL problem file is shown in Figure 3. This file contains the required sections of requirements, initial conditions, and goal conditions.

```
(define (problem kitting-problem)
 (:requirements :strips :typing)
 (:domain kitting-domain)
 (:objects r1 kt1 lbwekt1 lbwk1 wtable ptA ptB ptC
  partA-1 partA-2 partB partC eff1 eff2 effh1
  effh2 kins1)
 (:init  (rhold r1 nil) (effloc eff1 effh1)
  (effloc eff2 effh2) (not (isptempty ptA))
  (not (isptempty ptB)) (not (isptempty ptC))
  (onworktable wtable nil) (not (islbwektempty lbwekt1))
  (not (islbwkfull lbwk1)), (partloc partA-1 ptA)
  (partloc partA-2 ptA) (partloc partB ptB)
  (partloc partC ptC) (ktloc kt1 lbwekt1))
 (:goal (and (partloc partA-1 kins1)
  (partloc partA-2 kins1) (partloc partB kins1)
  (partloc partC kins1) (kinsloc kins1 lbwk1)))
```

Fig. 3. Excerpt of the PDDL problem file for kitting.

IV. CONCLUSIONS AND FUTURE WORK

In this paper we have presented the first knowledge model that is part of the IEEE RAS Ontologies for Robotics and Automation, Industrial Robotics subgroup on kitting. This abstraction begins with data that has been created by an expert user as a state variable representation and encoded into an OWL ontology. The knowledge is then automatically transitioned into a Planning Domain Definition Language that may be used by a class of planners to find a solution that will provide for actions that will transition the system for its initial state to a prescribed goal state.

This workstation is still very much a work in progress. The IEEE working group has an active mailing list and meets in person at both the IEEE ICRA and IROS conferences. At present, we are working on connecting the planned action sequence through the ROS control stack to our USARSim virtual world. As the knowledge representation is exercised, it is expected that shortcomings and missing data will be detected. Our representation will be updated as necessary to cope with these developments. In addition, the representation will be expanded to include metrics that allow us to represent not only the the information necessary for the construction of a kit, but also for the representation of the quality of the finished kit and the kit building process.

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