A Formal Model of Affordances for Flexible Robotic Task Execution

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Abstract. One of the key reasoning tasks of robotic agents is inferring possible actions that can be accomplished with a given object at hand. This cognitive task is commonly referred to as inferring the affordances of objects. In this paper, we propose a novel conceptualization of affordances and its realization as a description logic ontology. The key idea of the framework is that it proposes candidate affordances through inference, and that these can then be validated through physics-based simulation. We showcase the practical use of our conceptualization by means of demonstrating what competency questions an agent equipped with it can answer. The proposed formal model is implemented as a TBox OWL ontology of affordances based on the DOLCE Ultra Light + DnS foundational ontology.

1 INTRODUCTION

Everyday activities, such as preparing meals, setting tables and cleaning up, take place in non-standardized environments and can vary greatly in their procedural execution. Enabling artificial robotic agents to perform such tasks under realistic conditions goes far beyond programming them to perform a specific action sequence in a given environment. Some consider the technological leap necessary to go from achieving a task to mastering an activity to be a pivotal challenge in cognitive robotics today [5].

Anyone waking up in a household that has not been visited before and entering the unfamiliar kitchen in the morning with the intention to make some coffee, would theoretically have to solve a problem that features an infinitely large search space. Nevertheless, no one would divide the kitchen into a grid and start searching for the coffee grounds, let us say, at square *A1*. Human agents would start looking for suitable containers within cupboards that are in reach of the coffee maker first. Additionally, in case the filters cannot be found at all, we would consider the use of suitable alternatives such as sieves, paper towels, or else.

In an effort to describe the interaction between living beings and their environment Gibson coined the term *affordance* stating that:

> ”The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. ” [10]

Gibson readily acknowledged the problematic ontological character of this concepts by continuing:

> ”...an affordance is neither an objective property nor a subjective property; or it is both if you like. An affordance cuts across the dichotomy of subjective-objective. [...] It is both physical and psychical, yet neither.” [ibid]

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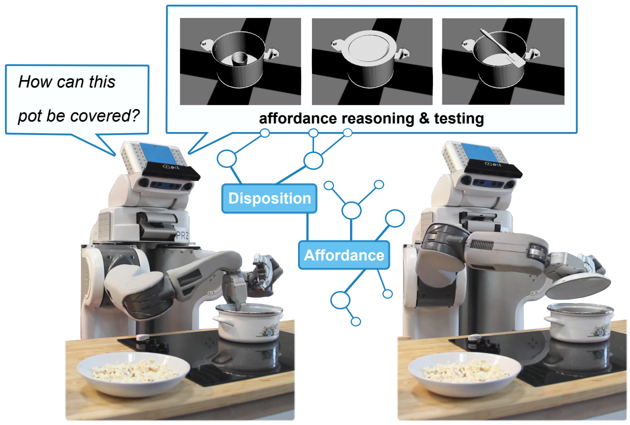

Figure 1. A robot that reasons about what can be used to cover a pot.

The central notion – the capability of living beings to interact with and change their environment are tightly linked to an ability to infer affordances – is undisputed. Additionally, this inference must be based on a coupling of our perceptions of the situation at hand to our knowledge of the world.

The relevance of affordances for autonomous robotics has been recognized by several authors [26]. The reason is that, once outside rigidly structured environments, an agent – biological or artificial – needs to adapt and to some degree improvise, or take advantage of, action possibilities that are conducive to its goals. This needs a theory of affordances, and a reformulation of current object-centric reasoning and planning around these concepts. Without affordance-based reasoning, a robot is, essentially, stuck into thinking about objects as in, *is there a lid around here?* With affordances, object uses and roles become more important, thus opening up a new avenue for more abstract thinking as in, *is there something that can cover a container around here?* Such an example is displayed in Figure 1.

Affordances are also important when taking the perspectives of other agents. Household service robots, for example, are often required to arrange an environment – e.g., by setting a table – such that the future actions of human users are enabled. Whether an arrangement is good or not depends on whether it provides the needed affordances for the future action.

In the following, we will give an overview of prior modelling approaches to motivate the congruencies and divergences of our work. Thereafter, we will present our descriptive theory of affordances and how it contributes to reasoning about finding and combining appropriate objects and discovering possible dispositions at hand. Lastly, some practical applications of our models will be presented.

2 PREVIOUS WORK

Modelling affordances has been a challenging problem for numerous years. As we seek to build our model on the DOLCE+DnS Ultralite (DUL) foundational framework [15], we will highlight prior approaches as they pertain to the DOLCE modelling paradigm. Other work concerning, for example, the learning of relational affordance models for robots [16], is independent from the respective modelling approach taken. Any of the following approaches could be populated with the learned affordances.

One attempt to model affordances within the DOLCE framework is as `Qualities` of a `Physical Artifact` as proposed by Ortmann and Kuhn [21]. This modelling approach assumes an affordance to be inherent in a given object (the afforder) and to exist independent of the other entities (the affordees) involved. However, if one models affordances as qualities, questions such as *what can something be used with so as to manifest an affordance* are out of scope; the answer requires functional relations between objects.

An alternative approach is to model affordances as `Events`, as proposed by Moralez [17], based on the idea that an affordance happens when the right objects participate in it. The problems that arise with this approach are, besides going against the fundamental construal of events, it also confuses affordances with the act of perceiving them. Agents do not just perceive, but also conceptualize affordances by exploiting similarities underlying classes of situations regardless of whether these situations have been perceived or are imagined.

Yet another approach has been to model functional affordances [2, 1, 3], which describe the typical affordances that an object provides, often because it is designed with particular uses in mind. The cited research highlights situations where substitutions of objects or actions are necessary, and describes how the substitution is guided by knowledge of functional affordances, conceptual similarity of objects or actions from a taxonomy, and a preference order on substitutions. The difference to our approach is that a functional affordance is, essentially, a property of an object; a cup is *for holding water*, and *for drinking from*. In our approach, an affordance is rather a descriptive context between several entities.

The model proposed in the following section seeks to remedy the shortcomings of the aforementioned approaches and is based on the dispositional theory of Turvey [25], in which a disposition of an object (the bearer) can be realized when it meets another suitably disposed object (the trigger) in the right conditions (the background). Toyoshima consequently presented an ontological ABox model for dispositions based on Turvey's insights [24].

However, as Turvey's approach bases on particular kinds of dispositions inherited by the environment, we want to point out that notions of affordances as a function of environmental properties have been criticized several times [22, 9] as the agentive aspect is ignored – i.e. what is available to the agent. Chemero, for example, defines affordances as relations between abilities of organisms and features of the environment [9]. This definition has also been extended with a notion of interaction based on the view proposed by Norman, who puts the visibility of an object's affordance at the center [20]. While we regard this view as appropriate for the perspective of human-computer interaction and design, the dispute with Gibson's view that an affordance is there whether an agent can perceive it or not has not been resolved [19]. In the model proposed herein, as we will elaborate below, an environmentally facilitated affordance exists when it can be conceptualized by an agent as such.

3 THE DESCRIPTIVE AFFORDANCE THEORY

The dispositional theory of Turvey states that a disposition is *the property of a thing that is a potential* [25]. We are only interested in dispositions that enable robots to perform tasks so we can be more specific regarding the *potential* of dispositions.

Definition 1 *A disposition is a property of an object that can enable an agent to perform a certain task.*

It is important to note that we view a task as a conceptualization of an event, abstracting away from particularities of its occurrence by only referring to roles objects need to take during the task. For example, the actual event of an object leaving a hand and landing on the floor can be construed as accidental dropping or intentional throwing of that object. Fundamentally, dispositions are absolute properties and, therefore, not contingent on a given context. We consequently view a disposition as a quality of the environment that is implied by the existence of the object that carries it. Regardless of the exploitation of an object disposition in a given task, the disposition is there as a quality of that object.

We view affordances as descriptions of what objects in the environment offer to the agent, and that conceptualize tasks afforded by them. Hence affordances exist independently of the agents' ability to manifest them, they are inherited from what the environment offers. However, an affordance is not a *property* of the environment but rather describes how an agent may make use of some property of the environment by executing the task that is defined by the affordance.

Definition 2 *An affordance is the description of a disposition.*[4]

Each disposition is described by an affordance that defines the task afforded by the disposition. An apple, for example, has a disposition that affords us to eat it. The task defined by this affordance includes, for example, the role *edible*, and another role *consumer*. We distinguish between the role of the carrier of the disposition (the bearer), and the role of the object that is afforded by the disposition (the trigger), and assume that any disposition is described by exactly one affordance that defines both roles.

The manifestation of an affordance is a situation that satisfies the affordance, meaning that an action was performed that executes the afforded task with appropriate objects taking roles during that action. However, the afforded task may need to be decomposed into several sub-tasks, or executed in different ways depending on, for example, the ability of the agent, or availability of objects. Hence, the way an afforded task is to be executed by an agent is not implied by the affordance, so the task execution can be described by several alternative plans that define the afforded task in different ways.

Dispositions can be seen as the objective analog to capabilities for agentive entities. Therefore, objects can be the bearer of dispositions while agents can have capabilities. Consequently, we propose to also view the `Capability` concept as a type of quality inherited by the agent that carries it. However, we do not consider the `Capability` concept in the scope of this paper. Our model extends previous ones that also take Turvey as a starting point [22, 9, 24] by situating dispositions in the so-called *ground ontology* and connecting them to affordances that are part of the *descriptive* branch of the ontology [15]. As we will show below, this decoupling gives the model a level of flexibility analogous to the flexibility gained by the decoupling of actions from tasks [8].

[4] Please note that this definition is open to manifestations of affordances that take place without agentive entities involved, e.g, due to a serendipitous event involving inanimate objects, but as this bears no relevance to our domain, we focus on those affordances that enable agents to perform tasks.

3.1 Affordance Concept

Let us first formalize the `Disposition` concept. Fundamentally, it is a property of the object that is the bearer of the disposition. This relationship between bearer and disposition is denoted by the relation symbol *hasDisposition* (HAS_D). For the sake of saving space, we refer to the affordance concept by the letter `A`, and to the disposition concept by the letter `D`.

$$\begin{aligned}
\texttt{D}(x) &\rightarrow \texttt{Quality}(x) && (1)\\
\texttt{D}(x) &\rightarrow \forall y(HAS_D(y,x) \rightarrow \texttt{Object}(y)) && (2)\\
\texttt{D}(x) &\rightarrow \exists! y(HAS_D(y,x)) && (3)\\
\texttt{D}(x) &\rightarrow \exists! y(DESCR(y,x) \wedge \texttt{A}(y)) && (4)\\
DESCR(x,y) &\rightarrow \texttt{Description}(x) && (5)
\end{aligned}$$

We model dispositions as qualities (1) carried only by exactly one object (2,3), and described by exactly one affordance (4). The *describes* relation (*DESCR*) holds between a description (e.g., an affordance) and entities that are conceptualized by the description (5).

Affordances define task and roles afforded by the disposition they describe. Specifically, we distinguish between roles afforded to the bearer of the disposition, and the ones afforded to the trigger. Consequently, we introduce two relations *definesBearer* (DEF_B) and *definesTrigger* (DEF_T) that link an affordance to the respective role.

$$\begin{aligned}
DEF(x,y) &\rightarrow \texttt{Description}(x) \wedge \texttt{Concept}(y) && (6)\\
DEF_B(x,y) &\rightarrow DEF(x,y) \wedge \texttt{A}(x) \wedge \texttt{Role}(y) && (7)\\
DEF_T(x,y) &\rightarrow DEF(x,y) \wedge \texttt{A}(x) \wedge \texttt{Role}(y) && (8)
\end{aligned}$$

The *defines* relation (*DEF*) holds between a description (e.g., an affordance) and a conceptualization (6), both *definesBearer* and *definesTrigger* are subproperties of this relation (7 and 8). The *definesTask* relation (DEF_{Tsk}) is formalized analogously.

Finally, we formalize the `Affordance` concept by axiomatizing its relationship to dispositions described, and concepts defined by it.

$$\begin{aligned}
\texttt{A}(x) &\rightarrow \texttt{Description}(x) && (9)\\
\texttt{A}(x) &\rightarrow \forall y(DESCR(x,y) \rightarrow \texttt{D}(y)) && (10)\\
\texttt{A}(x) &\rightarrow \exists! y(DEF_{Tsk}(x,y) \wedge \texttt{Task}(y)) && (11)\\
\texttt{A}(x) &\rightarrow \exists! y(DEF_B(x,y) \wedge \texttt{Role}(y)) && (12)\\
\texttt{A}(x) &\rightarrow \exists! y(DEF_T(x,y) \wedge \texttt{Role}(y)) && (13)\\
\texttt{A}(x) &\rightarrow \forall c,y(DEF_B(x,c) \wedge CLS(c,y) \rightarrow && (14)\\
&\qquad \exists z(DESCR(x,z) \wedge HAS_D(y,z)))
\end{aligned}$$

We view affordances as descriptions (9) that only describe dispositions (10). An affordance defines exactly one task (11), and two roles for bearer and trigger of the disposition (12,13). Axiom 14 is an identity constraint that restricts the bearer role to the objects that carry a disposition that is described by the affordance, meaning that the role may only *classify* (*CLS*) these objects. These relationships between concepts defined in our theory are depicted in Figure 2.

We further say that a disposition *affords* the task and roles defined by the affordance that describes the disposition. Different specifications of this relation are useful when particular disposition types are axiomatized. Consequently, we introduce a relation *affords* (*AFF*), and sub-relations *affordsBearer* (AFF_B), *affordsTrigger* (AFF_T), and *affordsTask* (AFF_{Tsk}).

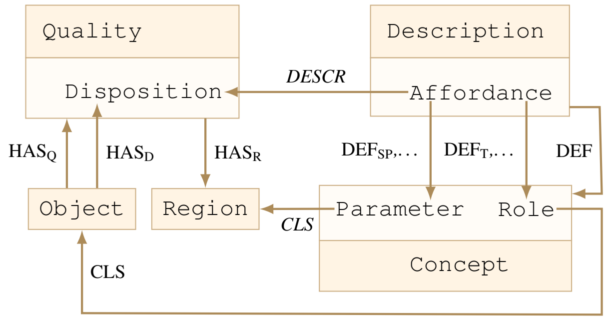

Figure 2. Relationships between affordances and dispositions in our theory.

$$\begin{aligned}
AFF(x,y) &\rightarrow D(x) \wedge \texttt{Concept}(y) && (15)\\
AFF(x,y) &\rightarrow \exists a(DESCR(a,x) \wedge DEF(a,y)) && (16)\\
AFF_B(x,y) &\rightarrow AFF(x,y) \wedge \texttt{Role}(y) && (17)\\
AFF_B(x,y) &\rightarrow \exists a(DESCR(a,x) \wedge DEF_B(a,y)) && (18)
\end{aligned}$$

The *affords* relation links dispositions and concepts (15). Any concept afforded by a disposition is defined in an affordance that describes the disposition (16). Specifications of this relation further constrain the type of the afforded concept (17), and how the concept is related to the affordance that defines it (18). The formalization of other sub-relations, i.e., *affordsTrigger* and *affordsTask*, is done analogously.

The manifestation of an affordance (*MAFF*) is, in our view, a situation (*SIT*) that *satisfies* (*SAT*) the affordance describing the dispositions that are included in the situation (19). More concretely, it is a situation where an agent executes the task defined by the dispositions by following a plan (which is a description) involving objects playing certain roles and regions setting specific parameters for that execution. Hence, situations in which affordances are manifested also satisfy the plan that the agent executes (20).

$$\begin{aligned}
MAFF(x) &\rightarrow \exists! y(SAT(x,y) \rightarrow A(x)) && (19)\\
MAFF(x) &\rightarrow \exists! y(SAT(x,y) \rightarrow P(x)) && (20)
\end{aligned}$$

The formal plan is referred to as P above. A formalization of plans that describe tasks afforded by dispositions is out of scope of this paper, as well as a full formalization of affordance manifestations. Above axioms only serve the purpose to provide a starting point for investigating this concept at a later point.

3.2 Disposition Hierarchy

We classify dispositions according to different roles for bearer and trigger they afford. Axiom 12 and 13 ensure that there is exactly one role for them such that disposition types may use an universal quantification axiom to constrain the roles.

One example is the `Blockage` disposition (*BLK*). We view it as the disposition to prevent others from accessing, leaving, or seeing a restricted space or group. It affords the bearer role `Barrier` and the trigger role `Blocked`.

$$\begin{aligned}
\texttt{BLK}(x) &\rightarrow \texttt{D}(x) && (21)\\
\texttt{BLK}(x) &\rightarrow \forall y(AFF_B(x,y) \rightarrow \texttt{Barrier}(y)) && (22)\\
\texttt{BLK}(x) &\rightarrow \forall y(AFF_T(x,y) \rightarrow \texttt{Blocked}(y)) && (23)
\end{aligned}$$

Hence, *blockage* is a disposition (21) that only affords the *barrier* role for the bearer of the disposition (22), and only the *blocked* role for the trigger (23).

Another class of dispositions refers to the potential to modify aspects of others. We say that objects that afford us to change others inherit the Alteration disposition (ALT). Alteration is primarily inherited by designed tools and devices such as a dishwashers that afford to clean cutlery, or freezers that afford to regulate the temperature of objects. However, a counterpart of the Alteration disposition may be inherited by objects that tend to undergo certain modifications. This is, for example, the dirty cutlery after dinner that affords us to clean it, or the melting ice cream that affords us to put it back into the freezer. The main difference is that these counterpart dispositions afford different roles for the bearer and the trigger of the disposition, namely that the bearer of one disposition needs to take the role of the trigger in the other.

Tasks defined by the affordance describing an alteration disposition include an additional parameter, the setpoint (SP), that qualifies the targeted change, for example, that dirty cutlery affords to change its Cleanliness quality such that the cutlery is not qualified as *dirty* anymore. The actual quantification of the targeted change may differ from one property type to another such that it cannot be axiomatized on the more general level. However, sub-classes of the Alteration disposition can be classified according to the type of quality that is afforded to be altered, and axiomatized with a more concrete notion of what values the property may take.

$$\mathtt{SP}(x) \rightarrow \mathtt{Parameter}(x) \quad (24)$$
$$\mathtt{SP}(x) \rightarrow \forall y(\mathit{CLS}(x,y) \rightarrow \mathtt{Region}(y)) \quad (25)$$
$$\mathtt{SP}(x) \rightarrow \exists y(\mathit{DEF}(y,x) \rightarrow \mathtt{A}(y)) \quad (26)$$

Hence, setpoints are used to classify regions that quantify the targeted change (25), and there exists some affordance that defines each setpoint (26).

Based on the *setpoint* notion, we axiomatize the relations DEF_{SP} and AFF_{SP} analogously to the other variants of the *DEF* and *AFF* relations, and assert that alterations also afford a setpoint parameter:

$$\mathtt{ALT}(x) \rightarrow \exists! y(\mathit{AFF}_{SP}(x,y)) \quad (27)$$

The other two types of dispositions considered in our model are Connectivity and Containment. The Connectivity disposition of an object affords to connect others with it, such as a hook that affords to hang up objects. Linkage is a more specific type of connectivity that implies a stronger connection between bearer and trigger such that they resist spatial separation to some extend. Another variant of connectivity is the Support disposition that affords, for example, stabilizing a posture, or controlling an object. The Containment disposition affords the Container role for the bearer of the disposition, however, without implying a portal that can be used to insert items into the container. Insertion is a variant of containment that, in addition, affords a *portal* role.

As the goal of this work is to introduce and evaluate a modelling approach and corresponding ontology pattern for affordances, we employ some concrete examples from our domain. Given the multitude and diversity of tasks executed by human and artificial agents, we expect a fully fleshed out model to include a small set of high-level dispositions that feature increasingly specific sub-dispositions. However, as with the discussion on the number and nature of image schema [11], that are influenced by our perception and interactions with the physical world, we expect an exhaustive model to be attainable, and moreover learnable [12], given a suitable target representation as the one proposed here.

3.3 Inherited Dispositions

The dispositions of an object are usually inherited from the class the object belongs to. The apple that affords us to eat it, for example, does that because the individual apple belongs to a category of objects that all inherit this disposition, for example, the category of comestible objects. Note that we may, for example, also restrict the Perishable quality of objects that afford us to eat them to values that indicate that the food is not spoiled.

For example, let us consider a dirty piece of cutlery in the kitchen (denoted DC). With dirty we mean the object has a quality Cleanliness that takes some value from a region Dirty whose members only quantify dirty objects.

$$\mathtt{DC}(x) \iff \exists q(\mathit{HAS}_Q(x,q) \land \mathtt{Cleanliness}(q)) \land \exists r(\mathit{HAS}_R(q,r) \land \mathtt{Dirty}(r)) \quad (28)$$
$$\mathtt{DC}(x) \rightarrow \exists! y(\mathit{HAS}_D(x,y) \land \mathtt{C}_0(y)) \quad (29)$$

Axiom 29 states that such dirty cutlery affords to clean it. HAS_Q refers to the *hasQuality* relation that links objects and their qualities, and HAS_R refers to the *hasRegion* relation that links qualities to their value.

Next, we formalize that *demand to be cleaned* means to alter the cleanliness quality of the demanding object to some value from a region Clean whose members only quantify clean objects, and that the disposition of the dirty cutlery to be cleaned (denoted as $\mathtt{C}_0$) affords this task where the bearer of the disposition takes the role of the Cleaned object.

$$\mathtt{C}_0(x) \rightarrow \forall y(\mathit{AFF}_{Tsk}(x,y) \rightarrow \mathtt{CT}(y)) \quad (30)$$
$$\mathtt{C}_0(x) \rightarrow \forall y(\mathit{AFF}_T(x,y) \rightarrow \mathtt{Cleaner}(y)) \quad (31)$$
$$\mathtt{C}_0(x) \rightarrow \forall y(\mathit{AFF}_B(x,y) \rightarrow \mathtt{Cleaned}(y)) \quad (32)$$
$$\mathtt{C}_0(x) \rightarrow \forall y,z(\mathit{AFF}_B(x,z) \land \mathit{CLS}(z,y) \rightarrow \mathtt{DC}(y)) \quad (33)$$
$$\mathtt{C}_0(x) \rightarrow \forall y,z(\mathit{AFF}_{SP}(x,z) \land \mathit{CLS}(z,y) \rightarrow \mathtt{Clean}(y)) \quad (34)$$

The task afforded by the disposition is referred to as CT (short for *cleaning task*). Analogously, we can state that a dishwasher (denoted DW) has the disposition to clean dirty cutlery.

$$\mathtt{DW}(x) \rightarrow \exists! y(\mathit{HAS}_D(x,y) \land \mathtt{C}_1(y)) \quad (35)$$

The disposition of the dishwasher to clean cutlery (denoted $\mathtt{C}_1$) can be seen as the counterpart of the disposition $\mathtt{C}_0$ of the cutlery to be cleaned. Meaning that both dispositions afford the same task, and that the bearer and the trigger roles are reversed. However, the disposition of the dishwasher is more restrictive as it also constrains the trigger object of the disposition to be *dirty cutlery*. The disposition of the cutlery, on the other hand, does not constrain the class of the trigger object used to clean it.

$$\mathtt{C}_1(x) \rightarrow \forall y(\mathit{AFF}_B(x,y) \rightarrow \mathtt{CT}(y)) \quad (36)$$
$$\mathtt{C}_1(x) \rightarrow \forall y(\mathit{AFF}_B(x,y) \rightarrow \mathtt{Cleaner}(y)) \quad (37)$$
$$\mathtt{C}_1(x) \rightarrow \forall y(\mathit{AFF}_T(x,y) \rightarrow \mathtt{Cleaned}(y)) \quad (38)$$
$$\mathtt{C}_1(x) \rightarrow \forall y,z(\mathit{AFF}_B(x,z) \land \mathit{CLS}(z,y) \rightarrow \mathtt{DC}(y)) \quad (39)$$
$$\mathtt{C}_1(x) \rightarrow \forall y,z(\mathit{AFF}_T(x,z) \land \mathit{CLS}(z,y) \rightarrow \mathtt{DW}(y)) \quad (40)$$
$$\mathtt{C}_1(x) \rightarrow \forall y,z(\mathit{AFF}_{SP}(x,z) \land \mathit{CLS}(z,y) \rightarrow \mathtt{Clean}(y)) \quad (41)$$

3.4 Implementation

For practical use of our theory, we provide a reference implementation as *Ontology Web Language* (OWL) ontology. In the process of creating an *OWL 2 DL* ontology that implements our theory, we have converted the axioms listed in this paper to Description Logics (DL). More specifically, to the *SROIQ(D)* fragment of DL. We were able to formulate each of the axioms except of the identity constraint (Axiom 14) which is not expressible in OWL 2 because co-reference of an entity with different roles cannot be expressed. This means that the OWL ontology does not enforce that only the bearer of a disposition may take the bearer role defined in the affordance.

Let us consider again the example of a dishwasher affording the task to clean dirty cutlery. One aspect of it is that the dishwasher affords the `Alteration` of the cleanliness quality of cutlery. Another aspect is that the cutlery can be inserted into it which is a disposition with type `Insertion`. This can be written in *Manchester OWL Syntax* as:

Listing 1. Dishwasher dispositions

```
Class: Dishwasher
SubClassOf:
   hasDisposition exactly 1 Insertion
   hasDisposition exactly 1 (Insertion
     and (affordsTrigger only
          (classifies only DirtyCutlery)))
   hasDisposition exactly 1 Alteration
   hasDisposition exactly 1 (Alteration
     and (affordsTrigger only
          (classifies only DirtyCutlery))
     and (affordsSetpoint only (Clean
          and (isRegionFor only Cleanliness))))
```

This is not a complete list of all dispositions a dishwasher has, however, it serves the purpose to give an intuition about how the dispositions of objects are formalized in OWL using our affordance theory.

The reference implementation is publicly accessible [5]. It is part of a larger framework of ontologies. The overarching goal of the framework is to enhance robot decision making capabilities, and therefore to make the plans robots execute more general and re-usable. This is achieved by providing a *tell* and *ask* interface to interact with the knowledge content of the ontologies which is realized by the KnowRob knowledge base [23].

4 THE THEORY AT WORK

In the following section, we showcase the practical work and the ensuing flexibility that our model facilitates in the domain of cognitive robotics for everyday activities [5]. Goal of this larger research undertaking is to depart from single task robotics, where a robot has to be trained to cover an object provided a designated pot and lid are at hand, to a flexible mastery of a basic activity, such as covering. For this we need, first of all, a flexible means for dispositional matching, which is a dispositionally qualified object, such as a container. We seek for dispositional counterparts and respective objects that can play the corresponding roles, for example, to serve as a cover. This type of flexible common-sense reasoning will provide potential triggers for specific bearers and *vice versa*, but will not guarantee that a specific instance of that object type will actually work in creating the needed affordance. Therefore, in a second step, we test via simulation how our potential afforders and affordees work together.

[5] https://github.com/knowrob/ease_ontology/blob/ecai2020/owl/EASE-OBJ.owl

4.1 Dispositional Matching

One of the most essential aspects covered by our model is that dispositions have a counterpart, another disposition whose carrier is *compatible* with the disposition offered by some other object. We say that objects have a *dispositional match* in such a case. The match is not dependent on agentive aspects, it is only derived from properties of the objects carrying the dispositions. Hence, the existence of a match is not equivalent to say that some agent can actually use both objects with each other – this further depends on the agents' capability to execute the task afforded by the dispositions.

Both dispositions contributing in a match afford their own individual task (i.e., an individual that is an instance of the `Task` concept). One aspect of a dispositional match is that both individual tasks are instances of the same task concept. The other aspect is that any object contributing in a match must be compatible to the trigger role afforded by the disposition of the other object. A match exists in case these axioms can be added to the knowledge base without making it inconsistent. This can be written as displayed in Algorithm 1.

Algorithm 1: Dispositional Matching

Input : Two disposition individuals d_1 and d_2, and a consistent ontology $\mathcal{O} = (\mathcal{A}, \mathcal{T}, \mathcal{R})$ where $\mathcal{A}$ is an ABox, $\mathcal{T}$ is a TBox, and $\mathcal{R}$ is a RBox.

Output: *True* in case there is a dispositional match between d_1 and d_2, otherwise *false* is returned.

$o_1 \leftarrow \mathit{hasDisposition}(d_1)$
$o_2 \leftarrow \mathit{hasDisposition}(d_2)$
$tsk_1 \leftarrow \mathit{affordsTask}(d_1)$
$tsk_2 \leftarrow \mathit{affordsTask}(d_2)$
$tri_1 \leftarrow \mathit{affordsTrigger}(d_1)$
$tri_2 \leftarrow \mathit{affordsTrigger}(d_2)$
`/* The axiomatization of a dispositional match. */`
$\mathcal{A}_1 \leftarrow \mathcal{A} \cap \{tsk_1 \doteq tsk_2, \mathit{CLS}(tri_1, o_2), \mathit{CLS}(tri_2, o_1)\}$
$\mathcal{O}_1 \leftarrow (\mathcal{A}_1, \mathcal{T}, \mathcal{R})$
`/* Is` $\mathcal{O}_1$ `inconsistent? */`
if $\mathcal{O}_1 \models \top \sqsubseteq \bot$ **then**
  return *false*
else
  return *true*
endif

The match between tasks is axiomatized as $tsk_1 \doteq tsk_2$, meaning that tsk_1 and tsk_2 are the same individual. This is inconsistent, for example, in case tsk_1 and tsk_2 are individuals of *disjoint* classes. Hence, we assume a task taxonomy that includes disjointness axioms between tasks sharing a direct superclass. However, the axiom $tsk_1 \doteq tsk_2$ still holds in case tsk_1 is an instance of a class that is a direct relative of the class instantiated by tsk_2.

The other two axioms are used to test whether the object carrying the counterpart disposition is a valid assignment for the *CLS* role that links the trigger role to the objects that are classified by this role. This would be inconsistent, for example, in case the bearer of the disposition, the disposition itself, or the affordance describing the disposition constrains the type of object that may take the trigger role to one disjoint from the type of the potential trigger object.

We further assume that the bearer role is a valid role to take for the bearer of the disposition. The identity axiom (14) would contradict an invalid assertion. However, our OWL implementation does not contain this axiom such that this relation must be enforced elsewhere when this implementation is used.

4.2 Competency Questions

The goal of a reasoning system is to infer useful answers to questions an agent faces. In the case of our affordance and dispositions model, these are questions related to item usage and action potentialities.

Our general procedure to answer such questions is to create an ontology importing our theory of dispositions and affordances, and our ontology of objects, and add axioms to define concepts relevant for a particular query. These axioms can be generated via Generic Ontology Design Patterns [14] written in generic DOL [18]. E.g., the query concept in Listing 3 is instantiated from the pattern in Listing 2.

Listing 2. A pattern in Generic DOL to create a query concept for affordance testing

```
pattern AffordanceQuery[Class: D; Class: T] given EASE =
Class: WithAffordance[D,T]
EquivalentTo:
  DesignedArtifact and
  hasDisposition some (D and
    (affordsTrigger some (classifies only T)))
```

What can be used for a particular purpose? The main question is, given an affordance, what is a combination of objects needed to manifest it. This is important for an autonomous robot for several reasons. First, the robot might need to formulate intermediate goals and plan sub-tasks to achieve them, and to have flexibility it must not be limited by blind, hard-coded object choice; rather, it should be able to select appropriate objects for the goals it sets for itself. Second, commands given by a human, or instruction steps meant to teach how to do something, are often ambiguous about tools to use – because such commands or instructions were typically meant for other humans, who do have the cognitive machinery to go from a requested action potentiality to the items needed to manifest it.

To answer such queries, one would add a concept for classes of objects that can be, for example, the bearer of a disposition to manifest an affordance. A DL reasoner can then be queried for subsumption.

Let us consider the following example: we are looking for an object that is the bearer of a `Tempering` disposition – that is, it can subject some `Substance` to a set temperature.

Listing 3. OWL expansion of the Generic DOL instantiation AffordanceQuery[Tempering;Substance], yielding a named concept to query for object classes that can be the bearer of a disposition to manifest an affordance

```
Class: WithAffordance_Tempering_Substance
EquivalentTo:
  DesignedArtifact and
  hasDisposition some (Tempering and
    (affordsTrigger some (classifies only Substance)))
```

Running a DL subsumption query on our objects and affordances ontology, augmented with the definition of the concept listed above, produces that `Refrigerator` and `HotPlate` are sub-concepts, that is, they can be used to temper substances.

What can this be used for? A second competency question an agent such as an autonomous robot must answer is, given an item, what can it be used for. This is an important step for a robot to understand an environment in terms of the affordances it actually provides, which in turn is useful when it has to answer how to manifest a particular affordance, or to verify that the environment has been set up in such a way that affordances are available to another agent. Specifically, this question addresses the issue of identifying dispositions of items in the surroundings of the robot.

Semantic maps of environments are often populated with objects and annotations about them, including dispositions. If this is available, then querying for the known dispositions of an object is simply a lookup in a semantic map. However, the information in the semantic map may be incomplete, such as when seeing a new item, in which case one must reason based on TBox axioms.

Let us consider the following example: The robot is looking at an item it recognizes as a dishwasher, and asks itself what dispositions it might have. As before, the general approach is to define a concept to add to the ontology for a reasoning query, but there is a complication. The fact that a disposition is not mentioned in the definition of an object concept does not mean some individual object will not have the disposition. Instead, the query concept is about what disposition an object must have to be a member of its class.

Listing 4. An example named concept to query for disposition classes that are borne by an object

```
Class: WithoutDisposition_Dishwasher_Insertion
EquivalentTo:
  Dishwasher and (hasDisposition only (not Insertion))
```

Running a DL subsumption query on our dispositions and objects ontology, augmented with the definition of the concept listed above, produces that this concept is subsumed by `Nothing`, therefore every individual dishwasher must allow some kind of items to be inserted in it. A similar query with a concept `WithoutDisposition(Dishwasher,Movable)` does not return that the query concept is empty, meaning there may be individual dishwashers that cannot or should not be moved.

What can this be used with? This competency question tackles the fact that, typically, the manifestation of an affordance needs appropriate combinations of objects – that is, objects with sufficiently matched dispositions. In some sense, a cookie cutter is an object allowing the shaping of (some) other objects – but it cannot be used to shape a block of wood. This is the other step towards building an affordance-aware understanding of the robot's environment.

Consider the following example: we want to test whether a particular item can be tempered by the `Refrigerator`.

Listing 5. An example named concept to query whether an object class can be the trigger for a disposition borne by another object class

```
Class: IsTrigger_PancakeMix_Tempering_Refrigerator
EquivalentTo:
  PancakeMix and (isClassifiedBy some
    (isTriggerAffordedBy some
      (Tempering and
      (isDispositionOf some Refrigerator))))
```

Running a DL subsumption query on our dispositions and objects ontology, augmented with the definition of the concept listed above, proves this concept is not subsumed by `Nothing`, therefore the `PancakeMix` can be tempered by the `Refrigerator`. A similar test run with `Stove` as the item to try and temper produces that `IsTrigger(Stove,Tempering,Refrigerator)` is a subconcept of `Nothing`; this is because the `Stove` is not a `Substance` or `FoodItem`, which are the only classes in our model, a `Refrigerator` can temper.

What cannot be used to manifest a particular affordance? This, and likewise negative versions of the other previous competency questions, are important to consider because the knowledge of the world is likely incomplete; not being able to prove, via inference, that a disposition is available or an affordance manifestable does not mean this is actually so. It simply means the agent does not know enough to prove, and perhaps might find it illuminating to test, whether in simulation or in the real world.

Sometimes however, a robot does know enough to prove that an object does not have a particular disposition, or that a combination of objects cannot be used to manifest an affordance. These negative results can be used to avoid unnecessary tests via other techniques to detect what dispositions and affordances are available.

For example, let us consider that we need to cover a pot, and it is not clear which items might provide the necessary disposition to achieve this. However, we know that whatever is a potential cover must afford moving by a human agent using their hands only. We can then define a query concept similar to the first competency question (Listing 3).

Listing 6. An example named concept to query for object classes that can be the bearer of a `Movable` disposition triggerable by a humanoid hand

```
Class: WithTriggerable_Movable_HumanoidHand
EquivalentTo:
  DesignedArtifact and
  hasDisposition some (Movable and
    (affordsTrigger some
      (classifies only HumanoidHand)))
```

To query for which object classes do *not* obey the requirement, it is not enough to just add this concept to the ontology; instead, named concepts for intersections of the query concept in listing 6 with object classes need to be included, for example:

Listing 7. An example named concept to query whether a particular object class has a disposition triggerable by another

```
Class: TriggerableBearer_Movable_HumanoidHand_Refrigerator
EquivalentTo:
  Refrigerator and
  WithTriggerable_Movable_HumanoidHand
```

Then, a DL reasoner can be queried for subsumption, and object classes that are now inferred empty correspond to items that cannot be used to manifest the desired affordance.

4.3 Simulation-based affordance testing

To test whether a particular affordance is made available by a set of objects, we use the simulation approach described in [4]. A *scene*, that is, the world of a physics engine, is populated with objects placed such that various initial relations hold between them; the simulation runs for a few seconds, and the resulting timeline is then analyzed to check whether several conditions hold.

A description of the initial setup of the scene, the simulation behavior, and timeline conditions is called an *execution context*. Table 1 describes an execution context for testing a *coverage* affordance, where coverage is understood as blocking all paths to the interior of a container. The notation is that of CRAM [6] *designators*, that are key-value pairs qualitatively describing objects, locations, and actions. Designators are *resolved*, that is, converted into quantitative descriptions, via a mix of reasoning processes such as generation and validation of position samples.

Testing in simulation is done because, ultimately, the behaviors that use an affordance are the behaviors of physically embodied agents, and thus physical and geometric considerations become important. However, simulation is computationally intense, and without some knowledge in the system it is not clear a-priori which object combinations are worth testing. A theory of affordances can narrow down the list to a small number of plausible candidates, leaving the simulation as an arbiter for cases that are ambiguous or unknown yet in the affordance theory.

Table 1. Execution context for testing affordance: cover

SCENE SPECIFICATION(CONTAINER=X, COVER=Y)
(AN OBJECT (TYPE Y) (AT (A LOCATION (ON (AN OBJECT (RECOGNIZABLE-AS CONTAINER) (TYPE X))))))
PLAN TO RUN
(PERFORM (A MOTION (TRAJECTOR (AN OBJECT (TYPE PELLET))) (SOURCE (A LOCATION (OUTSIDE (AN OBJECT (RECOGNIZABLE-AS CONTAINER))))) (DESTINATION (A LOCATION (INSIDE (AN OBJECT (RECOGNIZABLE-AS CONTAINER)))))))
TO CHECK ON SIMULATION TIMELINE
(NOT (HOLDS ?TL (AND (WORLD ?W) (OBJECT ?W (AN OBJECT (TYPE PELLET) (AT (A LOCATION (INSIDE (AN OBJECT (RECOGNIZABLE-AS CONTAINER)))))))) (AT :FINAL)))

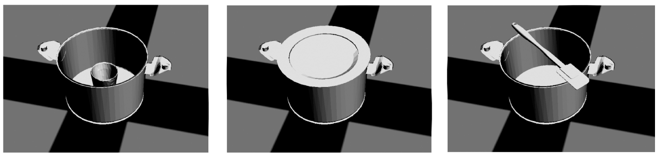

Figure 3. Pairs of items in the coverage affordance test: pot and cover attempt by cup, plate, and spatula respectively. Images show final states of the world, where a final state is computed by letting the simulated world run through several physics steps.

5 CONCLUSION AND FUTURE WORK

In this paper, we have proposed the *Descriptive Affordance Theory* – a theory, inspired by Turvey's notion of dispositions, that attempts to capture the descriptive nature of affordances. We have shown, by using an OWL ontology implementation of our theory, that models of the theory can be used to answer a set of questions highly relevant in the domain of autonomous robotics. We believe that such a theory of affordances is an important vehicle to reduce the programming effort needed to deliver robots that autonomously perform many tasks in many different environments in a flexible manner.

The proposed theory opens the doors for significant future research directions. First of all, we have only concentrated on object-centric aspects, that is, properties of objects and what they afford. We have stated that we also see the *capabilities* of agents as qualities, but we have neither included a theory of capabilities nor discussed the embodiment of the agent in the scope of this work.

Concerning the former initial work has been presented that aligns very well with our descriptive approach to affordances [13]. As for the latter, embodiment is a crucial aspect in robot task execution as well, because slightly different movements can have dramatically different consequences. Affordances may also allow and constrain the execution of motions in certain ways which also is a pertinent subject for future work. Ultimately, we see the need to establish a set of well-founded modular theories for the cognitive building blocks for flexible, adaptive and robust behavior, such as image-, force dynamic- and x-schema [7].

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