Systematizing Gibsonian affordances in robotics: an empirical, generative approach derived from case studies in legged locomotion

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***Abstract*— A Gibsonian theory of affordances commits to direct perception and the mutuality of the agent-environment system. We argue that there already exists a research program in robotics which incorporates Gibsonian affordances. Controllers under this research program use information perceived directly from the environment with little or no further processing, and implicitly respect the indivisibility of the agent-environment system. Research investigating the relationships between environmental and robot properties can be used to design reactive controllers that provably allow robots to take advantage of these affordances. We lay out key features of our empirical, generative Gibsonian approach and both show how it illuminates existing practice and suggest that it could be adopted to facilitate the systematic development of autonomous robots. We limit the scope of projects discussed here to legged robot systems but expect that applications can be found in other fields of robotics research.**

I. INTRODUCTION

A. *Affordance-based design of robot behavior*

An *affordance* is an opportunity for action [1]. Roboticists build autonomous systems that accomplish tasks by taking appropriately coordinated actions in an environment. We can conceive of a project in autonomous robotics, then, as that of designing a robot that can appropriately exploit the available opportunities for action relevant to accomplishing the specified overall task or tasks. Conceiving the design problem this way, we have two dimensions of control: the objects to be acted upon [2], or the agents acting upon them.

In structured settings such as factories, the complexity of the design problem has promoted approaches that treat these dimensions independently. Both affordances and agents are modularized in the interest of reconfigurability, scalability, and customizability [3]. Object design and machine capabilities are matched up through adherence to standardized interfaces, mitigating the complexity of design by direct specification of agent-environment integration. Agents benefit from such a prescriptive design by explicitly representing the environmental affordances and executing explicit plans to recognize and respond to them. Of course, even in the most structured settings, the illusion of complete control at design time is succeeded by intricate statistics-driven interventions at execution time pitting productivity against quality [4].

In contrast, consider a collaborative team of humans and robots performing fieldwork in a desert [5]. The environment is highly unpredictable, and even the robot may not behave predictably: end effectors break, and sensors can be damaged in the field. Clearly, in general, attempting to produce desired behaviors by precisely controlling and modeling the environment, then using an intricate recreation of a task in an agent's associated internal representation in order to execute it, is empirically unworkable. It is computationally costly, inherently specialized, and inevitably brittle.

Equally unworkable is the opposite extreme of design: A dogmatic commitment to reject internal representation altogether [6], using only layers of reactive architectures to attempt to confer robustness [7]. This approach may be sufficient for certain tasks in specific settings, but is unnecessarily limiting, and does not confer robustness even in those cases if the layers are not well composed.

Thus, there is need for more considered approaches which promote formal reasoning about how agent architectures can recruit preexisting affordances in order to generate desired behaviors. We propose an empirically driven rather than dogmatically Gibsonian approach to design that uses structured compositions of sensory-driven controllers arranged to produce a coupled agent-environment system that achieves desired tasks. We build our research program on the two most vitally Gibsonian notions of affordance [8]: that perception is direct, with the consequence that we minimize representations where the task does not explicitly involve representation generation; and that the agent and environment comprise one indivisible system that admits analysis.

This approach has two benefits which are not immediately obvious. First, it facilitates exploration of empirical possibilities that are Gibsonian in spirit: What representations are *needed* to produce the desired behavior? And second, if effort need not be spent to create representations that are useful for the robot to perform its basic behaviors, then the effort can be spent to create useful representations for communication between collaborating robots and humans. For example, a map of the ground stiffness in different locations in the desert would be a very useful representation for a team of robots tasked with helping geomorphologists studying erosion [5]. It is still useful even if the robots are able to navigate and locomote with reactive control that allows each robot to continue functioning normally even when it loses signal connection to team members, damages an end effector, or experiences a sensor glitch.

In this paper we review specific design episodes from a longstanding program of research in legged robotics that implicitly investigates affordances in the more formal but empirically grounded way we endorse. This research seems not to have been noticed by – much less integrated into

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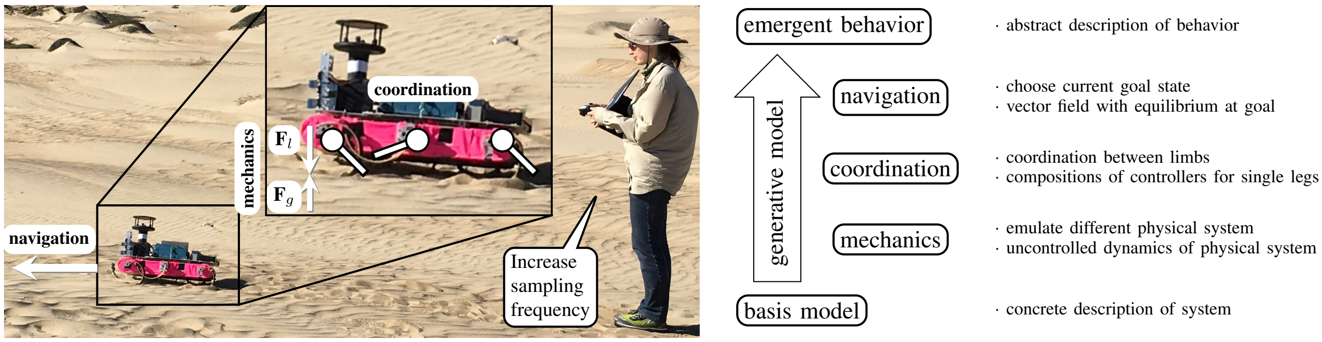

Fig. 1. We describe the role Gibsonian affordances have played in designing controllers at three levels (Section I-C). In this example task, a robot and human collaborate to perform fieldwork experiments in the desert.

– the broader Gibsonian robotics research program, which we anticipate is due to two causes. First, its authors have not emphasized perceptual processing or the concept of affordances, unlike other robotics researchers investigating affordances [9]. Second, its authors have instead emphasized mathematical proofs about the necessity or sufficiency for task achievement of some architectural feature relative to some hypothesized type of environment. These proofs give the designer (and potentially agent) diagnostic tools to assess whether a task is achievable, and if a failure occurs, why.

We aim to show that the Gibsonian features of this approach have demonstrated empirical payoffs for autonomous robots. In particular, we suggest that by explicitly articulating these features in line with the *generative methodology* of [10] we can facilitate the systematic development of robots that act still more autonomously in real-world environments – and explainably so, or refutably not.

B. Describing behavior at different levels of abstraction

Gibson described direct perception in two different, important respects. First, perception-as-sensation – that is, perception of information that is immediately accessible in the environment – may be sufficient to achieve the desired task. Perception may thus be "direct" in the sense of not needing further processing to perform its function. Second, perception-as-activity – that is, perception as something the whole agent does in its environment – can be understood as a dynamic relationship between the agent and environmental entities that together afford actions. It is thus "direct" in the sense that the perception can itself be understood and studied as a behavioral interaction. The extent to which internal modeling is necessary for perception-as-activity is an open empirical question [11] that we do not address here. Viewing perception-as-activity as one of many kinds of interactive behaviors belonging to an agent-environment system, we can formally reason about the coordination of subsystems using perception-as-sensation to produce complex behavior.

We adapt the generative methodology developed in [10] to describe an artificial system at multiple levels, respecting and relating these two senses of direct perception (see Figure 1). At the level of perception-as-sensation, we are concerned with what information is detected by a robot's sensors or what forces are produced by its actuators. The perception of a reactive planner [12] is "direct" in this sense. Description of an embodied artificial intelligence at this level provides a partial *basis model* of the physical robot and its environment.

At the level of perception-as-activity, we characterize the more abstract "higher-level" behavior that we are interested in artificially implementing. Description at the second level provides an *agent* or *emergent* model of the desired behavior abstracted away from the implementation. Behavior at this level is still integrated with the environment, but may be at larger temporal and spatial scales than basis-level components. Active perception [13] is "direct" in this second sense.

A "generative model" describes how features of the basis model affect features of the agent model – that is, how the components of the designed architecture and the relevant properties of the environment into which it is coupled affect the emergent behavior. Researchers programming robot behaviors create generative instances by organizing features of their robots and recruiting features of their enviroments. Formal analysis of these generative instances constitutes a generative model, which – if well furnished – can provide explanatory relationships between features of the basis and agent models. Separating discussion about these levels facilitates comparison of different technological approaches and projects, since the agent model can remain the same even with very different basis and generative models.

This framework was developed to enable theorizing about intentional behavior without requiring a commitment to mental representation [11]. We use it here to enable comparative discussions of robotics research, but do not insist on the same commitment to the emergent behavior having a particular relationship to intentionality on the part of the agent. This allows us to use the same framework to study both behaviors that are closely tied to the physical features of the agent and environment, and behaviors that are abstracted away from implementation. In this way, we can build "stacks" of relationships between the basis model and the emergent behavior, producing more sophisticated task performance with generative explanations of how more basic features contribute to overall agent-system performance.

C. Composing controllers with different bases to generate complex behavior

With this conceptual framework in place, recall the example of a robot collaborating with human scientists to perform fieldwork in the desert [5]. Under autonomous operation, the robot must detect and avoid obstacles and achieve goal states. The bulk of even end-to-end learners [14], [15], which control autonomous robots by relating pixel data from cameras or other sensors and directly to motor torques on the output side, do not include aspects of the motor controllers themselves, which are crucial for the overall emergent behavior. Even for a roboticist who is completely committed to training a single controller for the whole system, it is therefore natural to make a division at some level between the controller a researcher is currently developing and a lower-level controller that elicits the torques requested from the motors. Additionally, for any physically instantiated robot, the passive mechanics of the robot-environment system will also contribute to the system's overall behavior, and so a generative model of how passive mechanics and active motor control contribute to overall behavior is needed.

The importance of distinguishing basis and emergent models, with a generative model relating them, becomes even more important once we consider projects that compose multiple controllers in order to control the behavior of a robot-environment system from the bottom up in this manner. For example, a composition of controllers on a legged robot walking in a cluttered environment towards a goal might include controllers for the motors, controllers for individual leg positions and velocities, controllers to coordinate which legs act together or separately, controllers for the robot's overall direction and speed, a reactive controller for obstacle avoidance, and a global controller that informs the robot of its goal based on input from a collaborating human or other robot – or even additional global information (Figure 1). This composition of multiple controllers generates the agent-level behavior of the legged robot navigating its environment from the basis model of the various controllers and their coordinated interaction, and so plausibly a robot that responds to the distal, spatiotemporally larger, affordances in its environment. The need for a description of the emergent level distinct from the level of control and programming is crucial, regardless of the kind of programming or control involved, because the task is an agent-environment interaction and the elements of control and programming might or might not be directed at the specific level of task in question.

Iterative applications of the generative methodology can relate iteratively more basic processes to iteratively more emergent behaviors. Different levels of generative explanation may involve different concerns – as the relevant behaviors, and so agential or environmental features, vary – and so theoretical tools, as needed. Still, at a high degree of abstraction we can view all of their contributions as providing generative explanations. We can thus talk of concern-specific controllers with bases at different levels of abstraction from the physical implementation, which generative explanations can recruit. This approach allows us to start with relatively simply composed systems, and use a wide variety of tools and approaches at our disposal depending on specific problem needs at each level to build up more complex compositions of agent-environment behaviors.

Here, we examine projects with three kinds of concern-specific control – "mechanics," "coordination," and "navigation" – that serve as exemplars for our approach. These three are intuitively distinct enough to illustrate the usefulness of our approach for a variety of projects.

1) Mechanics: Within the "mechanics" level we describe both passive dynamics, i.e., the deterministic behavior of a system based only on physics,[1] and active dynamics, i.e., the behavior when when the robot is programmed to emulate another physical system. Consider a robot storing and releasing energy in springs in its legs while it runs [17], [18], [19]. The contributions by the springs to the motion of the legs come from the passive dynamics of the system.

Active dynamics are just like passive dynamics from the point of view of an observer looking at the physical behavior of the system, but active dynamics are generated by electromechanical components. For example, consider a robot leg with no springs that is set to hold a position using linear proportional-derivative (PD) control through a linkage that linearizes the motion of an end effector [20]. An observer with no information about the source of the forces produced at the end effector will not be able to distinguish the behavior of this system from a system with a physical spring in place of the electromechanical components.

2) Coordination: Most intuitively, the "coordination" level describes the coordination between limbs or other end effectors that produce whole-robot behaviors like taking a single stride [21], turning while running, or performing a transitional maneuver like a jump [22], [23]. We also include the coordination of multiple controllers for a single leg in this mode. For example, in a hopping or running robot, parallel composition of a pitch controller with a vertical height controller results in a robot that can run quite robustly, with speed and height control [24], [25].

3) Navigation: Controllers designed for the "navigation" level abstract away from the mechanics of the body and the coordination of its end effectors. Here, we examine navigation tasks in which the robot must avoid obstacles and make progress towards a goal state. For example, consider a robot attempting to climb to the highest point on a forested hill slope without colliding with any trees [26]. To achieve its task, the robot will need to coordinate its end effectors. Aspects of its body will react to the forces exerted upon it by its environment, either passively or actively. The "navigation" level of control, when considered alone, presumes robust coordination and mechanics basis levels such that it is sufficient to consider only the robot's current direction and speed, and maximum speed and turning capabilities.

[1] This has been more carefully articulated as "preflexes" – see e.g. [16]

II. CASE STUDIES

We summarize several research projects that demonstrate the usefulness of our empirically driven, generative Gibsonian approach. We discuss the variously related control loops introduced in the previous section to provide generative explanations of emergent behavior at the various levels of agent organization. For each project, we explain (1) the aspect of behavior under study (the "emergent level" description), (2) the relevant details of the specific robot and environment in the project (the "basis level" description), (3) the explanatory means by which the robot is able to perform this behavior competently in its environment in virtue of basis level features ("generative relationship"), and (4) we review the affordances considered in the design process. Finally, we discuss a project that combines Gibsonian-inspired control at some levels with symbolic processing at the most abstract level of control to demonstrate that a dogmatic commitment is not required to see benefit from using Gibsonian affordances in robot design.

A. Mechanics: Energetic cost of running on sand

This project is part of ongoing work to increase the capabilities of robots working alongside geoscientists studying erosion in environments like deserts [5].

1) Emergent behavior under study: The authors reduce the energetic cost of transport for a robot locomoting in the desert without sacrificing speed. Sand is highly dissipative, with a reaction force approximately linear in depth and quadratic in velocity, and no restoring forces [27].

2) Basis-level robot-environment pair: Minitaur [20] is a quadrupedal direct-drive robot that can be programmed for locomotion using parallel compositions of PD controllers that emulate damped springs [24]. Vertical hopping control for a single leg is thus decoupled from pitch control or coordination between legs. Deriving from Raibert's pioneering initial designs [25], a typical vertical hopping controller has a soft compliance gain during the first half of stance, allowing the leg "spring" to deflect under the weight of the body, and a stiff compliance gain during the second half of stance that causes the leg to extend and push the body up. When this type of controller is used on a compliant substrate like sand, the sudden injection of energy into the leg spring causes the foot to penetrate deeper into the sand at high velocity before the body moves up [28]. The authors target the vertical hopping controller and model its interaction with a bulk-behavior granular media model [27].

3) Generative relationship: Because the dissipation function of the sand is quadratic, most of the energy that a robot transfers to the ground through forces exerted at its foot will be quickly lost. The authors significantly reduce the energetic cost of a single jump to a given height [29], [28] by adding a virtual damping force in proportion to the velocity of intrusion of the foot into the granular media. The virtual damper is only active during the second half of stance, when the robot's leg spring switches from soft compliance gain to stiff. By punishing high-speed intrusions, this virtual damping force prevents the foot from entering the dangerous high-velocity regimes in which large amounts of energy are quickly transferred to the ground, significantly reducing the energetic cost of a single step without reducing apex height.

4) Use of Gibsonian affordances: The robot does not model the ground in any control loop running at the time of execution. Rather, at every timestep, it interrogates the state of the agent-environment system – its body and foot position and velocity – and reacts to this information by changing its leg gain in the next timestep. To implement this controller on a behaving robot, the robot need only have position encoders on its motors to sense leg length, and a sensor to detect the distance between the robot's body and the ground. To motivate the controller, the agent-environment system is considered as one indivisible system – a vertical hopper interacting with granular media. The quantity of interest is the work transferred between the robot's foot and the ground.

B. Coordination: Characterizing interactions with obstacles

Here we highlight an analytical contribution [30] to an ongoing project [31] examining the relationships between body, gait, and environment parameters that affect the center-of-mass trajectory of a robot.

1) Emergent behavior under study: Obstacles can be seen as opportunities for a locomoting robot to perturb its trajectory towards a desired direction. It may be possible to use perturbations from obstacles to purposefully modify a robot's trajectory by changing its gait parameters in order to interact with the obstacles at advantageous points in time during stance.

2) Basis-level robot-environment pair: HQ-RHex [30] is a small RHex-family robot with direct-drive legs. The robot's body is laser-cut from ABS plastic, making it easy to quickly change the aspect ratio of the body. The version used in these experiments has only four legs, which are coordinated into two gaits: bounding, in which the front two legs and rear two legs move together, and trotting, in which both diagonal pairs of legs move together. In both gaits, the two pairs of legs move out of phase with each other.

The environment is an obstacle field consisting of a series of half-round pipes placed on the ground. Each experiment consists of the robot running over the obstacle field perpendicular to the cylinders, starting from a variety of initial orientation angles.

3) Generative relationship: By systematically varying parameters governing body shape, log spacing, and leg coordination in both physical and simulation experiments, the authors demonstrate that the orientation angle of a robot's steady-state center-of-mass trajectory over an obstacle field can be predicted using closed-form analysis [30].

4) Use of Gibsonian affordances: This project highlights the mutuality of the agent and its environment: The steady-state behavior emerges from a relationship between the log spacing, the aspect ratio of the body, and the pattern of leg contacts with the obstacles.

As a larger goal, the authors aim to extract general relationships between parameters describing robot and environmental properties, including relationships between sizes or shapes of objects and their influences on a robot's locomotion like the forces and torques resulting from interaction. General relationships between properties and forces can then be programmed into the robot, and used in reactive control loops. For example, the inclination angle of the initial contact between the robot's leg and an obstacle can be used to predict the force exerted on the robot and thus the size of the trajectory perturbation [31]. Based on the current trajectory, the contact angle, and the desired direction of locomotion, a robot might then reactively either accept or reject the disturbance by adjusting its gait parameters.

C. Coordination: Manipulating a robot's body with its limbs

We highlight the first installment of a research program that uses insights from the manipulation literature to inform limb coordination for legged robots [32], [23], [33].

1) Emergent behavior under study: The authors sought to distribute effort between limbs while a robot is standing on rigid, uneven terrain. Uneven distribution of effort can cause motors to overheat, damaging the robot.

2) Basis-level robot-environment pair: XRHex [34] is a second-generation RHex robot [35], a six-legged machine with one rotational degree of freedom at each hip. The robot can measure the torque exerted by each hip by monitoring the current draw by the motor. Typically during a stand on rigid, flat ground, the robot is supported by all six legs pointing down, and all six legs exert the same torque. When standing on uneven ground, holding all legs in the same position requires much more torque from some motors than others.

3) Generative relationship: To develop the controller, the authors consider a robot with two legs: one at the front of the robot, and one at the back. The authors use the difference in the current draw between the motors in the front leg and the back leg as a proxy for the internal forces – the amount that the robot's legs are "fighting" each other in stance. These internal forces cause the robot to exert more torque than necessary in order to stand. At each timestep, the controller follows the negative gradient of this difference, minimizing the internal forces. In experiments on the physical robot, the controller is applied to each of the six legs independently.

There is an additional term in the controller which drives the average torque down, centering the mass of the robot over its toes. This reduces the overall force required to stand.

4) Use of Gibsonian affordances: This controller acts on an interaction between the robot and its environment and uses an aspect of this interaction as the controlled variable: the torque (current draw) at the hip joint. The indivisibility of the robot-environment system is thus respected. The relevant property is directly measured by monitoring the difference in current draw at the hips. The contributed controller is reactive, and the robot does not make use of an internal model of the environment to choose its foot placement.

D. Navigation: Reactive control on a global scale

This project demonstrates the use of a reactive controller for navigation in an unstructured, outdoor setting that violates the assumptions under which the controller is mathematically proven to succeed [26].

1) Emergent behavior under study: The authors develop a controller that governs navigation towards a goal in an environment with disc-shaped obstacles.

2) Basis-level robot-environment pair: RHex, introduced in Section II-C, is a robot with six C-shaped legs that are actuated by one rotational degree of freedom at the hip. The robot is tasked with navigating to the top of a hill in a natural forested environment. The shape of the robot's legs allows it to step through complex, unstable or broken surfaces including surmounting obstacles at or below the length scale of hip height [36]. This allows the robot to ignore leaf litter, small branches, and other debris for the purposes of its navigation task. The robot is equipped with an inertial measurement unit (IMU) with which to measure the local gradient, and a laser range finder with which to detect obstacles that are large enough to be likely insurmountable.

3) Generative relationship: The authors develop a reactive "navigation level" controller that takes information about the local gradient from the IMU and information about obstacles from the laser range finder at each timestep. The controller produces a summed vector indicating the direction that will increase the robot's height (reducing distance to the goal state) while avoiding the local obstacle.

Rather than commanding the robot's motors directly from this point, the controller issues commands constrained by a horizontal unicycle model of the robot. The commands are thus bounded by reasonable expectations of the translational and rotational velocities that the robot can physically execute. The authors provide formal guarantees for conditions under which the robot will achieve its goal, and perform experiments on a physical robot on forested hillslopes. During physical experiments, the authors logged thousands of bodylengths of successful autonomous climbing, including settings that violate the assumptions under which the guarantees are valid.

4) Use of Gibsonian affordances: The perception of both the direction towards the goal state (gradient) and the obstacles is direct, and the robot reacts to local information without developing a detailed model of the environment. The only aspects of an interal model of the environment that the robot uses are (1) an assumption that obstacles are disks, and (2) a short-term memory that prevents the robot from re-encountering a nearby obstacle that strays in and out of its field of view.

E. Navigation: Reactive controllers in abstract spaces

This project is part of ongoing work that applies reactive control to robots navigating in abstract spaces [37]. The abstract spaces are constructed using the assumption that the robot is encountering obstacles it can recognize.

1) Emergent behavior under study: As in the previous case study, the authors develop a controller that governs navigation towards a goal in an environment with obstacles. In this case, the obstacles are non-convex but familiar: The robot has a catalogue of objects that it can recognize, including pose, as soon as they are within sensor range.

2) Basis-level robot-environment pair: The controller is developed and tested in simulation, with a particle robot interacting with an unknown environment with nonconvex obstacles. Particle robot simulations are performed with two actuation methods: full actuation, and differential drive.

3) Generative relationship: The contribution of this project seems at first to be obviously non-Gibsonian, but it in fact demonstrates a method of interfacing between a deliberative planner and a reactive planner that allows the roboticist to gain some benefit from both approaches. The authors assume that non-convex obstacles can be recognized, and their pose estimated, once in range of a distance sensor. Once observed and recognized, the non-convex obstacles are contracted to a round shape using a continuous, invertible deformation. As they are detected, the contracted obstacles are added to a "model" space, which contains only round obstacles. The robot can then use a reactive controller to navigate through this model space. Commands to actuate the robot are obtained by first pulling the reactive controller's commands back from the deformed space into a physically relevant space containing all of the mapped obstacles ("mapped" space), and then through a controller to actuate either a fully actuated or a differential drive robot.

4) Use of Gibsonian affordances: This controller contracts recognized objects to small, round obstacles that can be reactively navigated around in an abstracted space. Making use of a library of recognized symbols in this way separates the problems of symbol grounding and navigation, reducing the complexity of the recognition task and increasing the robustness of the navigation controller by providing formal guarantees about its performance. The perception of the abstracted obstacles is direct.

F. Navigation: Layering deliberative and reactive controllers

This project is part of ongoing work that makes use of both reactive and deliberative controllers in order to gain some benefit from both approaches [38], [39].

1) Emergent behavior under study: This project is an example of an assembly task [40]: The robot must rearrange multiple objects in its environment to a desired configuration while encountering previously unknown obstacles.

2) Basis-level robot-environment pair: Theoretical work [39] was done on a simulated differential-drive robot. Physical experiments [38] were performed with a Minitaur rearranging wheeled stools in an unknown environment with obstacles.

3) Generative relationship: The robot is tasked with moving multiple objects to multiple goals. The task must therefore first be broken down into subtasks. A deliberative planner performs this function. To execute the subtasks, commands are passed to a separate reactive controller.

4) Use of Gibsonian affordances: The deliberative planning portion of this controller is not Gibsonian. However, the use of a reactive layer to handle obstacle interactions significantly simplifies the control problem, and allows the authors to provide formal guarantees about the conditions under which this controller should be expected to succeed. This is in line with our empirical, rather than dogmatic, Gibsonian approach. If non-Gibsonian deliberative planning is the most effective way to solve a problem (at least at this stage) we do not reject such strategies on principle. In this way, we can show how a deliberative approach can benefit from incorporating elements of our Gibsonian approach.

III. CONCLUSION

We have provided examples of robotics research incorporating strategies that take avail of Gibsonian affordances at multiple levels of control, from mechanistic force laws to controllers for navigation in unknown environments. In all of these examples, a controller perceives information in the robot-environment system and reacts to it directly. This is even true in the reactive controller that handles nonconvex obstacles outlined in Section II-E, if the "agent-environment system" is permitted to exist in an abstracted space.

Using reactive controllers allows robotics researchers to apply tools from dynamical systems theory, making possible formal guarantees for the situations in which a robot can be expected to succeed – or fail – at a task. By using reactive control rather than planning with a presumably accurate world model, robots are able to recover from perturbations, either from unmodeled external forces or sensor problems, so long as the robot's perturbed state is still within the domain in which the controller guarantees success. Even partial incorporation of Gibsonian behavioral programming confers some benefit for robustness and explainability (Section II-F).

Through these examples, we have illustrated how a Gibsonian approach to robotics research can be both theoretically illuminating and practically useful. We demonstrate how rational, empirical practice can apply Gibson's philosophy of affordances by using the generative methodology [10], which requires explicit articulation of the conditions for success of a perceptually direct strategy. Dogmatic "Gibsonianism" is not required to benefit from these applications. Considerations of engineering design and the practicability of abstraction from the environment at different levels of control can instead determine the mix of endowed prior knowledge, representation building, and sensory dependence. A commitment instead to a generative interpretation of affordances may facilitate reasoning about how to design complex behaviors from simpler reactive constituents. Robustness could then be guaranteed by the formal properties of specific compositions.

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