Generalising Human Demonstration Data by Identifying Affordance Symmetries in Object Interaction Trajectories

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Abstract— **This paper concerns modelling human hand or tool trajectories when interacting with everyday objects. In these interactions symmetries may be exhibited in portions of the trajectories which can be used to identify task space redundancy. This paper presents a formal description of a set of these symmetries, which we term affordance symmetries, and a method to identify them in multiple demonstration recordings. The approach is robust to arbitrary motion before and after the symmetry artifact and relies only on recorded trajectory data.**

To illustrate the method's performance two examples are discussed involving two different types of symmetries. An simple illustration of the application of the concept in reproduction planning is also provided.

I. INTRODUCTION

There has been much work in the way of enabling trajectory-level imitation in manipulators and humanoids [1] [2] [3]. By the term 'trajectory-level' we refer to the imitation of basic motions which guide a robot through its workspace to yield behaviours such as pouring water or tossing a ball. Common amongst many proposed imitation schemes is the problem of generating a reliable and useful behaviour model given very few actual demonstration recordings. Any consumer would likely not have the patience to record more than possibly ten demonstrations. It is also preferrable not to expect a user to provide too much additional information when interpretting their actions.

Another topic closely related to behaviour reproduction is behaviour recognition. As with imitation it is difficult to build a behaviour classifier given only a few examplar recordings. There are approaches where imitation and behaviour recognition are considered linked and, through simulation, recognition systems try to answer the question: 'If I were doing behaviour A in the current situation, would I be doing this?' [4]. If a user is executing an arbitrary behaviour in a different situation to the training scenes and such a scheme is applied, then the recognition system would have to try generalize its small set of demonstrations to answer that question.

This paper addresses the two problems simultaneously by proposing a scheme to identify symmetries in behaviour recordings in a household setting. These symmetries allow reduction in the dimensionality of the recordings so that in the lower dimension better models of behaviour can be constructed. They arise because man-made objects people typically interact with in day to day living are often designed using simple geometrical primitives, such as rectangles or circles, and simple articulation freedoms, such as hinges or prismatic joints. When people interact with these objects their behaviour reflects some of those objects' symmetry.

Consider Figure 1. In blue are two trajectories of a demonstrator's hand when opening the oven. Suppose that we are not aware of the oven or the door's hinge joint and we are modelling the behaviour of the demonstrator's hand. We would prefer a model which would consider the imagined trajectory (in red) as potentially equivalent to the blue trajectories. Of course, from two demonstrations it is difficult to assume that the trajectory in red is a viable option. Perhaps the handle is split in the middle. But, being aware of the potential equivalence of the red trajectory is an important step in generalizing this behaviour. This hypothesis could even then be tested by some robot that is modelling the behaviour.

This paper proposes that the red trajectory is potentially similar to the blue trajectories through identifying what we term an 'affordance symmetry'. The term affordance is, of course, used in the same manner as in the work of [5]. It refers to the implied function or interaction modalities of an object. In the example, the symmetry could be considered linear and is given by the fact that the hand trajectories projected onto a plane perpendicular to the edge of the handle lie precisely on top of each other when interacting with the oven. It could be argued that with a kinematic model of the oven such a 'symmetry' would be obvious, but in many interactions when the robot is unaware of an object's affordances identification of such artifacts can greatly improve trajectory models and allow some redundancy in task reproduction planning.

This paper proposes two things: Firstly, the concept of an affordance symmetry and its mathematical expression and, secondly, a means of identifying potential symmetries in trajectory recordings. The scheme used to identify potential symmetries is similar to the generalized Hough transform. Because it is impossible to be absolutely sure that a potential symmetry exists without a means to test it, verification is considered out of the scope of the paper.

The structure of the paper is as follows: Section 2 will discuss related work. The affordance symmetry concept will be presented in section 4. The concept and its performance will be illustrated with a number of experiments in the same section. Section 5 will apply the concept to behaviour reproduction. Conclusions and future work will be the topic

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Fig. 1. Hand trajectories for opening an oven show regions of high symmetry

of Section 6.

II. RELATED WORK

The concept of symmetry has found application in many fields not least of which are theoretical physics, crystallography and molecular biology. In computer vision, it has been applied to modelling human attention [6]. In psychology, symmetry has been found to be an important aesthetic for people. A study was conducted where faces were manipulated to appear more symmetrical. They were judged to be more attractive than the original faces [7]. In an experiment investigating the appreciation of symmetry in art, symmetrical patterns were found to be preferred over assymmetrical versions [8]. We propose to bring a form of this concept in trajectory modelling.

Determining invariance in sets of behaviour demonstrations is the subject of many imitation papers. Work by Calinon, et. al. [1] focuses of wrapping a corridor around demonstration trajectories in the form of a Gaussian mixture model. This corridor captures the allowable variance in different stages of a task. This approach is very successful in situations where the task is fairly specific such as painting a pattern and where the user is trying to demonstrate the task as consistently as possible. The framework, however, requires many demonstrations in tasks where variance in demonstration trajectories is large.

Another work which related to ours is Jäkel, et. al. [9]. Based on assumptions about the objects used in interaction their system attempts to establish volumetric constraints consistent with the demonstrations. An example would be that at a certain stage the open end of a bottle is over the open end of a cup. The constraints also have temporal ordering. In our work, we propose that often trajectory data need only be considered in a lower dimensional space. This concept may very well reduce the search space necessary for [9]. Also, combined with the Gaussian mixture model approach [1] we are enabling an imitation scheme with very few assumptions except that objects may have affordance symmetries that can be exploited.

There is growing interest in identifying object articulation freedoms visually [10] [11]. Once such freedoms are identified imitation of interaction with the object is greatly simplified. Although the proposed approach could be used to suggest such freedoms, it assumes much less knowledge of the environment. It uses just the recorded trajectories. Interaction between objects need not be identified and is especially useful in behaviours where interactions are difficult or impossible to identify.

The works [12] and [13] discuss various ways to determine coordinate frames of demonstrations to align trajectory recordings. Our work differs in that rather than looking for a specific frame in which trajectories appear to be consistent, we try to identify the redundancies of the frames.

There is work where rotational symmetries are identified in demonstration grasping motions, but they do not generalize the concept [14]. A method to generate similar demonstration trajectories given model trajectories which uses Gaussian Process Latent Variable Models has been proposed [15]. The approach parameterizes trajectories in the same manner as Schaal [3] and differs to the presented work in that we do not fit a simplifying attractor model to recorded data. This difference allows our approach to complement agnostically current methods in imitation.

III. DATA CAPTURE

All data shown in this paper was captured using an OptiTrack NaturalPoint motion capture system with 8 cameras and a frame rate of 100Hz. An object in the hand of a single human demonstrator is tracked using reflective stickers attached to the target object. To speed up processing the raw data was resampled so that only data points at least 4cm apart were taken. This also removed portions of recordings where the tracked object was stationary.

IV. AFFORDANCE SYMMETRIES

An affordance symmetry can be precisely explained as follows. Suppose several recordings of an object or end-effector's motion during some particular task are taken. It is assumed that the motion of the object is determined according so some flow in the dynamical systems sense. That is, the motion of the object is dependent on its position and time or

$$\dot{\bar{x}} = f(\bar{x}, t) \tag{1}$$

During some portion of all the trajectories the flow may exhibit a symmetry for some interval of time during the demonstrations. In this paper, we consider two symmetries: Firstly, a linear symmetry is defined by Equation 1 depending on only two dimensions in object position ($\bar{x}$). The oven door example mentioned above is an example of this. Secondly, we present the revolute (cylindrical) symmetry about some axis in space. This can be visualized as a simpler 2D flow revolved about the axis.

This paper proposes a manner of identifying such symmetries. There is an issue which makes the problem more difficult. If we look back to the oven example, it is possible for a person to slide his hand along the handle while opening the oven. He/she may do this to avoid an obstacle. This motion along the handle will, in general, not correlate with other demonstrations of opening the oven unless the obstacle is persistent. In identifying a affordance symmetry, it is perferred that the method be robust to such motions.

In our definition, an affordance symmetry consists of two, potentially nonlinear mappings: $T(\bar{x}, R, \Lambda)$ and

$G(\bar{x}, R, \dot{\bar{x}}, \bar{\omega}, \Lambda)$. Input $\bar{x}$ is a recorded point of a object's trajectory. R is the orientation rotation matrix of the object at that point, $\bar{\omega}$ is the change in rotation and $\dot{\bar{x}}$ is the velocity. The parameters of the symmetries are represented by Λ.

A measure of a symmetry's applicableness is given by counting the number of occasions

$$|T(\bar{x}_i, R_i, \Lambda) - T(\bar{x}_j, R_j, \Lambda)| < \delta \rightarrow \tag{2}$$

$$D(G(\bar{x}_i, R_i, \dot{\bar{x}}_i, \bar{\omega}_i, \Lambda), G(\bar{x}_j, R, \dot{\bar{x}}_j, \bar{\omega}_j, \Lambda)) < \epsilon \tag{3}$$

is true for a given symmetry and its parameters. This is similar to the generalized Hough transform. The ϵ and δ represent thresholds that must be chosen. Function $D(x, y)$ determines a distance metric between x and y. The Euclidean norm may not always be appropriate because direction of change is often more important. In the equation, x_i and x_j must come from different demonstrations.

To find a symmetry, the parameters, Λ are searched for a set that produce a significant maxima. This scheme takes a number of issues into account. Firstly, during a demonstration, the symmetry may not be adhered to for all time. For instance, a demonstrator may approach the handle in a completely arbitrary manner in the above example. During search for a symmetry, arbitrary motion will contribute to all variations of the symmetry parameters in a not specific way and thus will, on average, produce no artifact. If iterative closest point or such approaches were used to locate symmetries, arbitrary motion would be considered equally with points adhering to the symmetry and so will throw off the search.

Secondly, the scheme may identify several symmetries as separate extrema in a single pass and is thus not a restrictive single hypothesis approach. Lastly, the metric is very cheap to calculate especially if fast nearest-neighbor methods are used to identify points which satisfy the left side of 3.

A. *Linear Symmetry*

The oven example above is one of many examples where a linear symmetry exists. Others include: pressing of piano keys, cutting bread with a knife, planing a surface, wrapping a cable around a bobbin, sanding a surface with file, there are an endless number of examples of objects which exhibit linear affordance symmetries. The parameter of such a symmetry is a direction vector representing a normal to a plane onto which trajectory points are projected. The direction vector can be parameterized with two angles, θ and ϕ.

T can be determined by in the following way. We find

$$\bar{a} = \begin{bmatrix} \cos(\phi + \frac{\pi}{2}) \cos(\theta) \\ \sin(\phi + \frac{\pi}{2}) \\ \cos(\phi + \frac{\pi}{2}) \sin(\theta) \end{bmatrix} \tag{4}$$

and

$$\bar{b} = \begin{bmatrix} \cos(\phi) \cos(\theta + \frac{\pi}{2}) \\ \sin(\phi) \\ \cos(\phi) \sin(\theta + \frac{\pi}{2}) \end{bmatrix} \tag{5}$$

then if we consider just translation $T(\bar{x}_i, R_i, \Lambda) = T_m(\phi, \theta)\bar{x}_i$ and $G(\bar{x}_i, R_i, \dot{\bar{x}}_i, \bar{\omega}_i, \Lambda) = G_m(\phi, \theta)\bar{x}_i$ with

$$T_m(\phi, \theta) = G_m(\phi, \theta) = \begin{bmatrix} \bar{a}^T \\ \bar{b}^T \end{bmatrix} \tag{6}$$

To illustrate this type of affordance symmetry we consider the task of slicing a vegetable. Figure 2 shows the recorded trajectories. The regular straight paths of the knife can be seen in the middle of the plot.

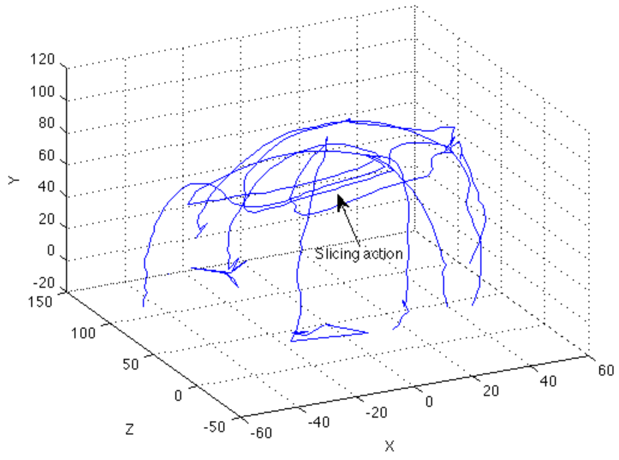

Fig. 2. Recorded trajectories of a knife slicing a vegetable.

To apply Equation 3, the distance function used was

$$D(\bar{x}, \bar{y}) = \cos^{-1}(\frac{\bar{x}}{|\bar{x}|} \cdot \frac{\bar{y}}{|\bar{y}|}) \tag{7}$$

The thresholds δ and ϵ was set to 6cm and 20 degrees respectively. Figure 3 is an intensity plot of the affordance symmetric metric for the linear case over a intervals of θ and ϕ. A maxima can be clearly seen (dark red) at $\phi \approx 0$ and $\theta \approx 2$. If we project the recorded trajectories onto a plane defined by these parameters the result is plotted in Figure 4.

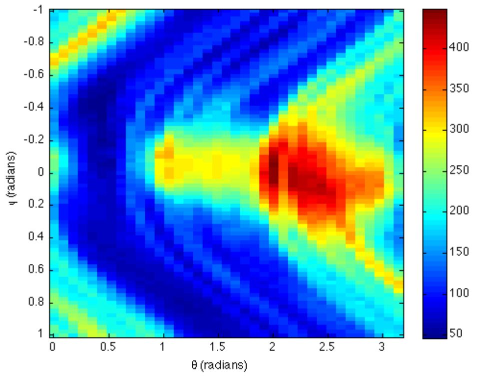

Fig. 3. Symmetry metric parametrized by ϕ and θ.

The cutting motions are placed on top of each other as we would expect. Figure 5 highlights the points that had Equation 3 true across all trajectories. The cutting segments

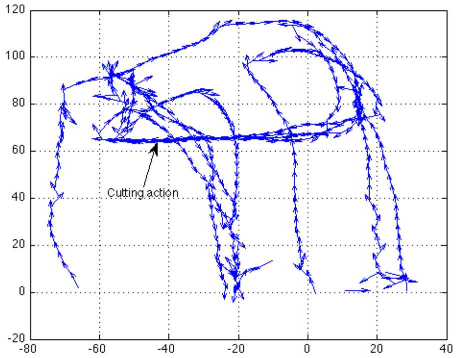

Fig. 4. Projected trajectories on the optimal symmetry plane.

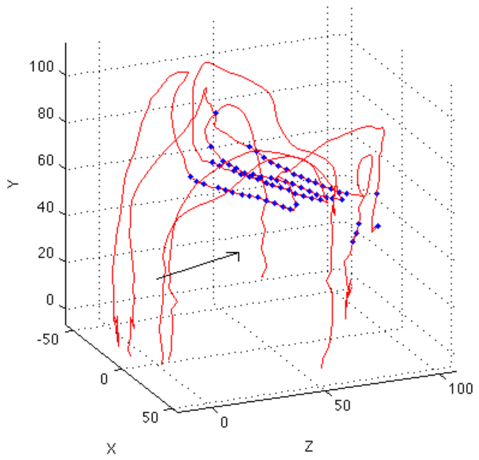

Fig. 5. Motion trajectories with points belonging to the symmetry labelled in blue. The black arrow indicates the direction of the symmetry.

are clearly visible. Other tasks with linear symmetries are shown in Figure 11. In the case of opening the laptop, two peaks were observed in the parameter space. The figure labels the points associated with the lower of the two.

B. Cylindrical Symmetry

The cylindrical symmetry is illustrated in Figure 6. The parameters of the symmetry are parameters for a line (black in the figure): a point in 3 space, $\bar{x}_{cs}$, and an axis direction vector, $\bar{a}$. The symmetry converts trajectory points into cylindrical coordinates around the line and keeps the height and radius's only. The azimuth is discarded. In this frame, the pouring task is equivalent no matter the approach.

If we are simply concerned with motion and not orientation in the object trajectory being modelled then the cylindrical symmetry may be expressed in the following way. For every trajectory point, $\bar{x}$,

$$\bar{r}(\bar{x}) = \frac{\bar{x} - \bar{x}_{cs} - (\bar{x} - \bar{x}_{cs}) \cdot \bar{a}\bar{a}}{|\bar{x} - \bar{x}_{cs} - (\bar{x} - \bar{x}_{cs}) \cdot \bar{a}\bar{a}|} \tag{8}$$

and

$$\bar{u}(\bar{x}) = \bar{a} \times r(\bar{x}) \tag{9}$$

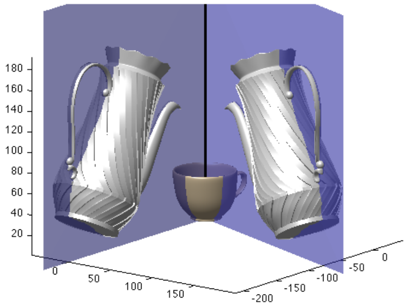

Fig. 6. The cylindrical symmetry in pouring with a teapot.

Then

$$T = \begin{bmatrix} \bar{r}(\bar{x})^T \\ \bar{a}^T \end{bmatrix} \tag{10}$$

is a 2x3 matrix and $G = T$. Figure 7 shows trajectories of a pizza being sliced on a table. If we assume that $\bar{a} = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$ and calculate Equation 3 over that perpendicular plane we get the image (plotted with matlab's imagesc) in Figure 8. The thresholds and distance function used were the same as in the linear case. As we expect the symmetry axis passes through the middle of the pizza.

Other tasks with cylindrical symmetries are shown in Figure 12.

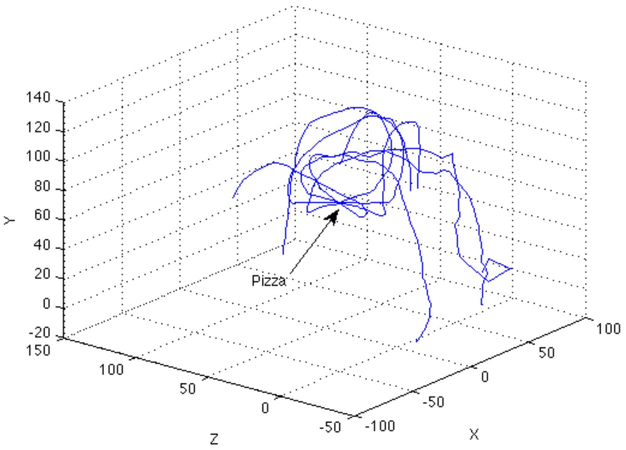

Fig. 7. Motion trajectories of a knife cutting a pizza.

Figure 9 is a plot of recorded points and their motion direction in the revolving redundancy plane. Figure 10 highlights the points that had Equation 3 true across all trajectories.

V. APPLICATIONS OF AFFORDANCE SYMMETRIES

To be absolutely sure that an affordance symmetry actually exists there must be some form of feedback, or a method to test the hypothesis. This is not the focus of the paper. We merely provide a means to identify a potential symmetry. This is analogous to a feature detector in computer vision which identifies potentially useful structures in an image.

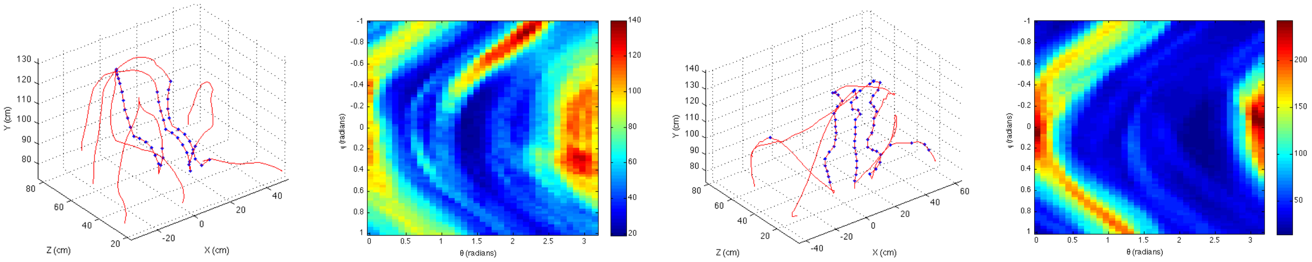

Fig. 11. Various other tasks with linear symmetries. On the left are recordings of a hand opening a laptop monitor. On the right are trajectories of a wobbly line being drawn down a board.

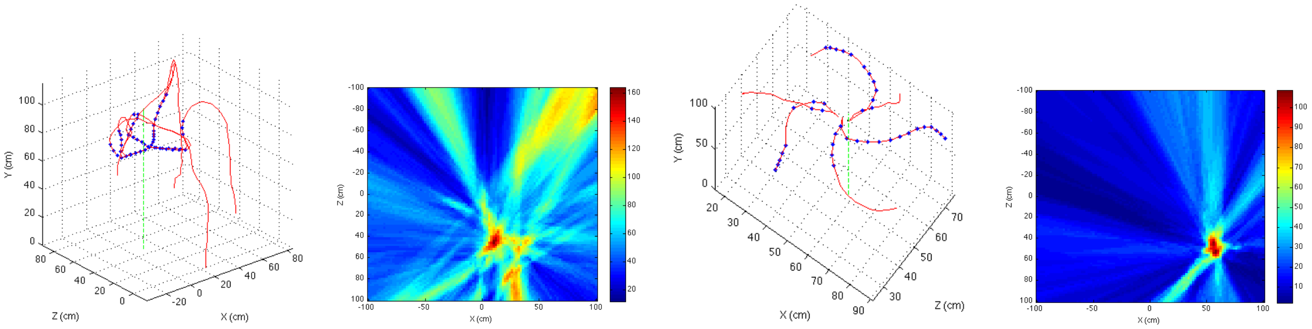

Fig. 12. Various other tasks with cylindrical symmetries. On the left are recordings of odd cutting pattern on a board. On the right are trajectories of a jar's contents being poured into a cup. The green dotted lines show the position and orientation of the axis of the symmetry in each case.

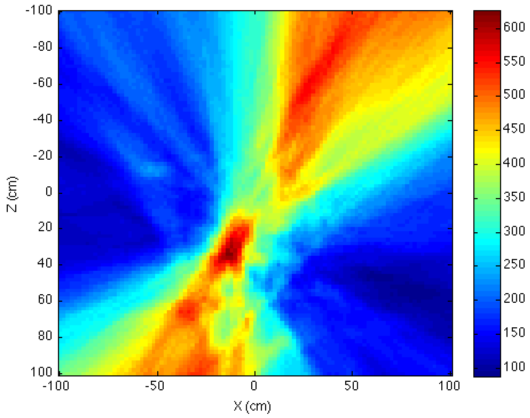

Fig. 8. Symmetry metric calculated over a plane through the fixed object.

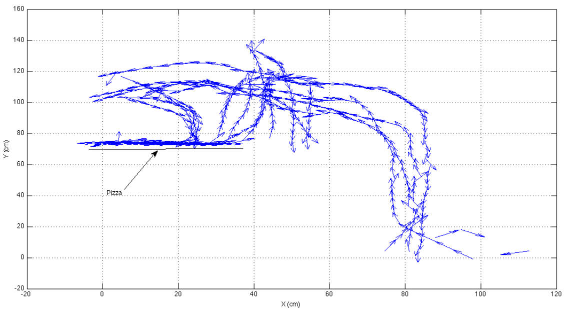

Fig. 9. Motion trajectories projected onto the redundancy plane around the symmetry point.

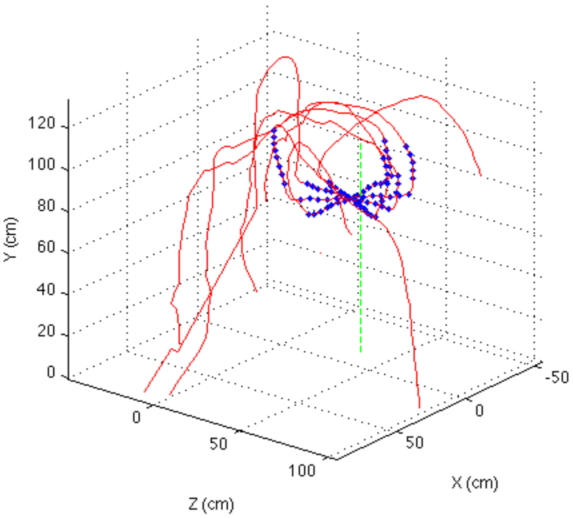

Fig. 10. Motion trajectories with points labelled when found to be part of the symmetry. The axis of symmetry is drawn in green.

But, once a symmetry is verified it can be used to provide a dimension of redundancy for a reproduction planner or a means to equate similar trajectories in classification. For the planning case, consider the example presented in subsection IV.A of slicing a long vegetable. If we take points that were in near contact with the table and project those that obeyed the identified affordance symmetry onto the plane perpendicular to the redundancy direction, we get Figure 13.

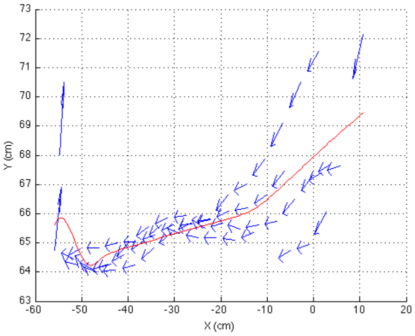

Fig. 13. The projected trajectories that agreed with the linear symmetry and are within contact range of the table in blue. An average trajectory in red

In the figure is an average trajectory generated using the approach of [1] shown in red. This approach relies on Gaussian Mixture Models (GMM) and Gaussian Mixture Regression (GMR). The reader is directed to [1] for a detailed discussion. If this average trajectory is placed along the redundancy direction within the variance shown in the recordings we get Figure 14. These trajectories represent alternative paths that could be supplied to a planner to cut the vegetable.

Also, portions of trajectories that do not exhibit symmetries in their motion are potentially arbitrary. It is, however, difficult to be certain of this without user assistance.

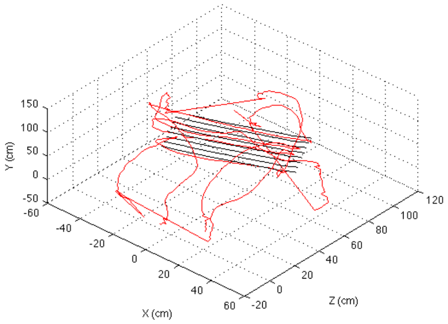

Fig. 14. Possible cutting trajectories in black over the recorded trajectories in red

VI. CONCLUSIONS AND FUTURE WORK

The concept of an affordance symmetry was presented along with a voting scheme to quantify the applicability of a hypothesized symmetry. The approach also allows the identification of portions of recorded trajectories that exhibited the symmetry. Two example symmetries, linear and a cylindrical, were presented and discussed to illustrate the principle. The approach successfully identified portions of recorded trajectories that exhibited symmetries.

To illustrate the application of the approach an example of producing reproduction plans using a affordance symmetry was discussed.

Future work will focus on a number of issues. Firstly, the proposed algorithm can detect a potential symmetry, but the existence of the symmetry cannot be verified without user assistance. Secondly, there may be many other symmetries that can be leveraged to compress complex behavior into lower dimensional trajectories. Also, the paper only considers displacement and not velocity or acceleration. In the act of stirring a cup of coffee, one could argue that only the circular motion of the spoon is important. We plan to explore whether this can be captured in the proposed framework. Lastly, the efficient exploitation of reduced behavior trajectories remains explored.

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