Trajectory Optimization for Predictable and Legible Motion

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For robots and humans to collaborate seamlessly in a shared workspace, robot motion must not be merely functional, but easily interpretable by the human collaborator observing the motion. Our work [1] formalizes motion in terms of the inferences that the observer makes, leading to two crucial properties — *predictability* and *legibility*: *predictable motion matches expectation, while legible motion conveys intent*. Based on this formalism, we propose optimization criteria that enable robots to generate predictable or legible motion (Fig.1, bottom), building on our prior work on functional gradient trajectory optimization [2] (Fig.1, top).

Formalism. As the observer is watching a trajectory, he continually makes an inference as to what the goal of the trajectory might be. In the psychology of action interpretation, this is referred to as a an "action-to-goal" inference[3], which in motion maps the Hilbert space of trajectories Ξ to the set of possible goals $\mathcal{G}$:

$$\mathcal{I}_L : \Xi \to \mathcal{G}$$

Legible motion enables an observer to *confidently* infer the *correct* goal configuration G_R after observing only a snippet of the trajectory, $\xi_{S\to Q}$, from the start S to the configuration at a time t, $Q = \xi(t)$: $\mathcal{I}_L(\xi_{S\to Q}) = G_R$. The *quicker* this happens (i.e. the smaller t is), the more legible the trajectory is.

On the other hand, if the observer knows that the goal is G_R, they anticipate what trajectory this might result in — an opposite, "goal-to-action" inference[3], which we denote here

$$\mathcal{I}_P : \mathcal{G} \to \Xi$$

Predictable motion is motion for which the trajectory $\xi_{S\to G_R}$ matches this inference: $\mathcal{I}_P(G_R) = \xi_{S\to G_R}$.

Optimization Criteria. If the observer sees the actor as a rational agent, applying the principle of rational action [3], then they expect the actor to be efficient. We model efficiency via a cost functional

$$C : \Xi \to \mathbb{R}_+$$

with lower costs signifying more "efficient" trajectories.

Being predictable means matching the user's expectation, $\mathcal{I}_P(G_R)$. Given C and applying the principle of maximum entropy, we model the user as expecting a trajectory ξ form the start configuration S to the goal G_R with probability $P(\xi) \propto \exp(-C[\xi])$, leading to an optimization criterion for predictability:

$$\textsc{Predictability}[\xi] = \exp\big(-C[\xi]\big) \tag{1}$$

For legibility, given an ongoing trajectory $\xi_{S\to Q}$, the observer infers a goal vial $\mathcal{I}_L$. In line with teleological

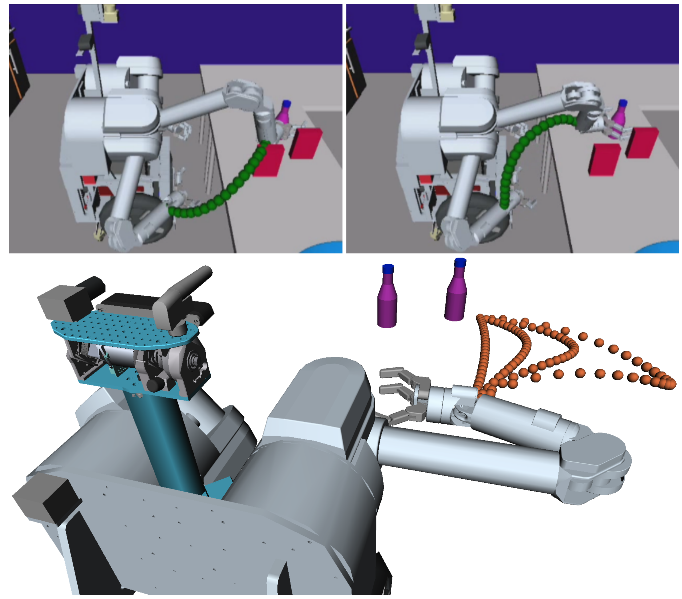

Fig. 1. Top: An initial trajectory on the left, and the resulting trajectory after optimization with Constrained CHOMP[2] on the right. Bottom: The trajectory as it is being optimized for legibility.

reasoning [3], we model this process as probability maximization: $\mathcal{I}_L(\xi_{S\to Q}) = \arg\max_{G\in\mathcal{G}} P(G|\xi_{S\to Q})$. Making a trajectory more legible means increasing the probability assigned to the actual goal G_R across the trajectory, with more weight being given to the earlier parts of the trajectory via a function $f(t)$ (e.g. $f(t) = T - t$, with T the total time):

$$\textsc{Legibility}[\xi] = \frac{\int P(G_R|\xi_{S\to\xi(t)})f(t)dt}{\int f(t)dt} \tag{2}$$

with the goal probability from [1]. While predictability optimizes C, legibility optimizes this more complex score, intimately related to C via this goal probability.

Given C, both Predictability and Legibility can be optimized using functional gradient descent techniques similar to CHOMP[2]. While in some cases C is known and the resulting trajectories are indeed predictable or legible [1] (Fig.1 shows a trajectory as it is being optimized for legibility), finding the right C in the general case remains an exciting area of future work, demanding the ability to learn this potentially non-convex cost function in high-dimensional spaces, as well as to customize it to a particular user.

References

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