Tempo Adaptation and Anticipation Methods for Human-Robot Teams

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***Abstract*—As technology advances, autonomous robots are becoming more prominent in our daily lives, and they will be expected to effectively work with groups of humans. In order to be effective teammates, robots need to be able to understand human team dynamics as humans do. This understanding will help robots to recognize, anticipate, and adapt to human motion. There exist many group interaction scenarios where the activities performed by the group members are not only synchronous, but also change their tempo over time. During these interactions, humans employ temporal *adaptation* and *anticipation* to coordinate with one another in a team. The goal of our work is to leverage these mechanisms to enable robots to better coordinate with human teams, with a particular eye toward understanding rhythm. We are developing methods for robots to better understand tempo changing behavior in teams, so that the robots can leverage this knowledge to coordinate with group members. This work will enable robots to recognize, anticipate, and adapt to human groups, and will help enable others in the robotics community to build more fluent and adaptable robots in the future.**

I. Introduction

Autonomous robots are adopting a variety of roles in our everyday lives. While robots have long been involved in assembly lines, automating and increasing efficiency of dexterous factory procedures [1], their use is growing in other areas where humans and robots are working together proximately. For example, robots are being used to provide physical and behavioral healthcare, both in clinical and homecare settings [2]–[4]. One goal of this trend for roboticists is to enable robots to fluidly, and longitudinally, act as independely and efficeintly as possible.

In a large majority of proximate settings, it is rarely one human and one robot. Instead, multiple people interact with one another and the robot simulatenously. Due to the challenging nature of these kinds of sensing situations, it can be difficult for a robot to perceive and understand all of the different movements of people to make effective decisions as a team mate.

Group interaction is an important aspect of human social interaction, and is an active area of research [5]–[8]. Most groups create a state of interdependence, where each member's outcomes and actions are determined in part by other members of the group. Understanding the internal dynamics of the group enables robot to interact more coherently and contingently with the other team members [9].

As humans, we encounter many group interaction scenarios where the activities performed by the group members are not only synchronous, but also change their tempo over time. Humans effectively time their actions to coordinate with others during everyday activities. Many researchers in the fields of psychology and neuroscience investigated how humans effectively time their coordinated actions with others, especially in a constantly changing environment [10].

One important aspect of successful coordination is precise motor timing. Sensorimotor synchronization is one of the skills that people employ to achieve this [10], [11]. Sensorimotor synchronization is considered to be a fundamental human skill, which is described as the temporal coordination of an action with events in a predictable external rhythm. Humans are skilled at sensorimotor synchronization even with a sequence that contains tempo changes [11].

Thus, while working alongside humans, if robots can understand rhythmic tempo changes, then they can adapt to those changes and adjust their actions accordingly. Understanding tempo changing behavior will enable us to build adaptable robots across a range of fields, from manufacturing and assembly processes, to assistive technologies to help people with disabilities. If robots can make sense of tempo changes as humans do, then it will be possible for them to adapt and adjust their motions while working with humans. This will help robots to become functional teammates to people.

Researchers in the fields of music, dance, neuroscience, and psychology investigated the sensory motor synchronization process of humans [10], [11]. These investigations included joint finger tapping with external rhythmic signals or with virtual characters, or joint drumming or joint dancing with other humans [12]. Researchers have found two main concepts that humans employ during coordination with other external rhythms: *temporal adaptation* and *temporal anticipation* [11], [13].

Despite the fact that humans perform temporal adaptation and anticipation during the synchronization of their movements, robots still do not know how to take advantage of these concepts. In this work, we plan to explore how

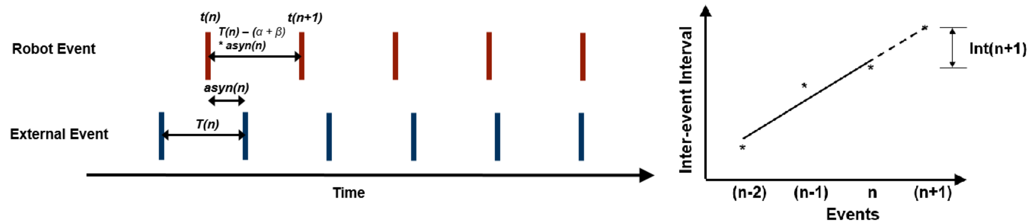

Fig. 1. Left: A representation of the adaptation process for the robot. The next event time of the robot is adapted from the timekeeper interval (T_n), the phase (α) and period (β) correction parameters, and the most recent asynchrony ($asyn_n$). Right: An anticipation method by linear extrapolation of inter-event intervals. The figures are adapted from [11].

robots can leverage these mechanisms to coordinate with other external rhythms. The goal of this exploration is to develop robust algorithms for robots that are sensitive to tempo changes during group activities, which will enable more fluent human-robot teaming. In this paper, we describe the initial development phases of these methods, and briefly discuss our experimental plans.

II. METHODOLOGY

We are designing and implementating a new algorithm for robots to interact within human-robot teams, which will be robust to changes in the tempo of a rhythmic signal. Drawing inspiration from computational neuroscience and psychology [10], [11], [14], we are designing an adaptable algorithm for robots to work in human-robot teams. This algorithm will have two main processes: an adaptation process, and an anticipation process.

A robot will use the temporal *adaptation* part of the algorithm to compensate for temporal errors that occur while synchronizing with an external rhythm. Using this adaptation mechanism, a robot will be able to overcome these challenges, and be able to change its motion timing to be coordinate to an external rhythm.

Extending work by Van Der Steen et al. [11], [14], we developed an adaptation process based on information processing theory [15], and extended it to work for multiple events encountered by robots during an activity. This approach uses a linear timekeeper model to compensate for timing errors on a cycle-by-cycle basis. In the timekeeper model, the error correction process can be described as a linear autoregressive process. Two separate adaptive processes, phase correction and period correction, have been proposed in information-processing theory [11].

During phase correction, only the timing of the next action is adjusted to compensate the asynchrony with a perceived rhythmic signal, but the timekeeper interval remains the same. During the period correction phase, the next action timing is adjusted, and the internal timekeeper setting is changed to compensate for the perceived asynchrony. Both processes independently modify the timing of the next action based on a percentage of the asynchrony [11], [14], [16].

The timing of the next event ($t_n + 1$) is based on the current action time (t_n), and a timekeeper (T_n) with the compensation of the phase (α) and period (β) correction by the most recent asynchrony ($asyn_n$) between the recent action and the perceived rhythmic signal [11]. In addition, the timekeeper period is compensated for the recent asynchrony and the period correction parameter (see Equation 1 and Figure 1-Right).

$$\begin{aligned} t_{(n+1)} &= t_{(n)} + T_{(n)} - (\alpha + \beta) * asyn_{(n)} \\ T_{(n+1)} &= T_{(n)} - \beta * asyn_{(n)} \end{aligned} \tag{1}$$

Additionally, the anticipation part of the algoritm will generate a prediction about the timing of the next action, so that it coincides with the timing of the next external rhythmic signal [11]. During this anticipation process, the human actions will be taken as the precursor to generate a prediction about the next timing of an event in the external rhythmic signal (see Figure 1-Left).

III. EXPERIMENTAL TESTBED

To test our algorithm, we have designed an experimental testbed involving a human-robot drumming team. Figure 2-Left shows the experimental setup. A group of humans drums together with a drumming robot. Music is played so that humans can drum at the same pace to an external rhythm. The group's goal is to drum synchronously with the external music, while coordinating with one another and the robot.

Three participants stand near a table. There is a drum pad and a drumstick in front of each participant. The robot is placed on the other side of the table. The participants are able to see the drumming of the other participants and hear drumming sounds. The robot's movements are visible from each participant on the other side of the table. (See Figure 2-Center).

A. The Drumming Robot

We built a robot capable of drumming with a human group. The robot is able to move a drum stick up and down at a rate of 4-5 Hz to hit a drum. This rate is very close to how fast humans generally can drum (5-7 Hz). Thus this robot is well-suited for our purpose.

The robot's effector (the drumstick) is attached to a Futaba Heli Rudder High-Speed servo motor with speed of 0.06 sec/60° and torque of 47 oz-in (3.4 kg-cm). In addition, the servo motor is connected to an Arduino Uno and a Renbotic Servo Shield. This arduino communicates with a computer via *rosserial*, and is used as an ROS node [17].

Fig. 2. Left: Experimental setup. A Kinect 2 tracks participant motion, as do pizeoelectric sensors in the drums. The robot uses these sensor data to decide when to hit its drum. Center/Right: Three participants drum with the robot during a pilot study. RGB and IR images are shown.

B. System Architecture and Activity Detection

We used a client-server architecture for data processing and controlling the robot that is very similar to what has been used in our previous experiments [9], [18], [19]. In this architecture, the client computers detect the events and their timings during the interaction, and send data to a server. The server then processes this data using the aforementioned adaptation and anticipation methods, and generates appropriate commands for the robot. It then sends the appropriate commands to the robot at the appropriate time.

To capture the activities of the participants, we used a Microsoft Kinect v2 sensor. We placed infrared markers at the top of the drumsticks to track the drumstick movements precisely. From the infrared images, we performed a blob tracking technique to track the top of the drumsticks. Figure 2-Right shows an infrared image during the drumming. For faster processing, we detected a small region of interest (ROI) for each drumstick positions, and only searched in that ROI in subsequent frames and updated the ROI positions.

When the humans start moving their drumsticks towards the drum pad, we detected the start of these events by tracking the infrared blobs. This provided an indicator that the humans were going to hit the drum. We used this as a precursor to inform the robot's movement.

To precisely measure when the humans and the robot hit the drum pad, we attached a piezoelectric sensor under each drum pad. These sensors attached to an arduino. Whenever the humans or the robot hit the drum pad, the arduino generated a "hit" event. The arduino ROS node published this event time, as well as the event type ('hit') instantaneously. The server listened to these messages. For now, our method incorporates visual and tactile rhythmic information, though in the future we plan to also incorporate audio.

IV. Experimental Plan

We are currently implementing the algorithm to test on the robot. Upon completion, we plan to perform a set of experiments, where the robot will drum with humans across a variety of rhythmic conditions. We will employ different aspects of the algorithm on the robot to investigate how well it performs in human-robot teams.

These studies will give us the opportunity to explore many dimensions of the process of fluent human-robot interaction, and identify which features will need attention during future robot algorithm development and interaction design.

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