A real-time synchronization algorithm between Text-To-Speech (TTS) system and Robot Mouth for Social Robotic Applications

F. Cid, R. Cintas, L.J. Manso, L. Calderita, A. Sánchez and P. Núñez

***Abstract*—Human-Robot Interaction (HRI) is one of the most important subfields of social robotics. In several applications, text-to-speech techniques are used by robots to provide feedback to humans. In this respect, a natural synchronization between the synthetic voice and the mouth of the robot could contribute to improve the interaction experience. This paper presents an algorithm for synchronizing Text-To-Speech (TTS) systems with robotic mouths. The proposed approach estimates the appropriate aperture of the mouth based on the entropy of the synthetic audio stream provided by the TTS system. The paper also describes the cost-efficient robotic mouth which has been used in the experiments. The system, which has been implemented in C++ and can perform in real-time, is freely available as part of the RoboComp open-source robotics framework. Finally, the paper presents the results of the opinion poll that has been conducted in order to evaluate the overall user experience.**

***Index Terms*—Mouth robotic, Synchronization, Interaction.**

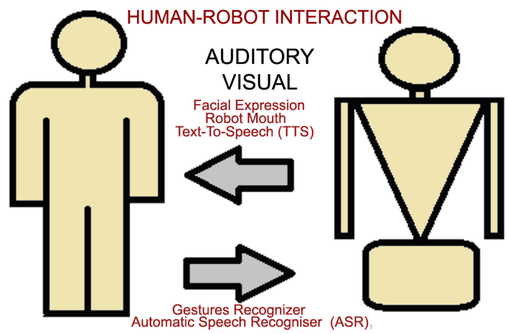

Fig. 1. HRI is usually based on visual and auditory information. For auditory information, depending on the communication direction, TTS or ASR systems are needed.

I. Introduction

During the last decade the robotics community interest in social robotics has grown dramatically. It is one of the robotics fields with more practical applications. Social robots are autonomous robots that interact with humans in daily environments, following human-like social behaviors (i.e. recognizing and expressing emotions, communicating, and helping humans or other robots). During last years the use of social robots has increased for a wide variety of applications (e.g. museum guide robots[1], [2], or assistive and rehabilitation robots[3], [4]). As in other fields of application, robots can offer several key advantages for rehabilitation, such as the possibility to perform (after establishing the correct set-up) a consistent and personalized treatment without fatigue; or its capacity to use sensors to acquire objective data, which can provide objective quantification of the recovery. However, in addition to providing physical assistance in rehabilitation, robots can also provide personalized motivation and coaching. Thus, it is interesting to study and develop effective mechanisms of interaction between patients and robots.

This interaction between human beings and robots, usually known as Human-Robot Interaction (HRI), represents a new challenge in the field of social robotics, resulting in new technologies and methods. Different robotic systems have been built and many studies have been conducted unveiling the importance of properly designed human-robot interaction strategies. Some of these works aim to achieve human-like robots in terms of shape [5]. However, shape is not the only important factor in order to develop good social robots, the capacity to behave similar to human beings and to adapt to their emotional state is also very important [6], [7]. Much work is being done in order to receive input data from humans (e.g. facial expression, skeletal modeling or speech recognition), but relatively little has been done regarding how robots should present information and give feedback to their users.

In order to interact with the environment, other robots and persons, social robots are equipped with multi-modal sensors like cameras, laser range finders or microphones. Using these sensors, social robots acquire and process the necessary data for establishing communication (e.g. where the interlocutor is, or what is hes/he saying or doing). On the other hand, robots working in human environments following social behaviors need different tools for interacting and exchanging information between the source and receiver of the message.

Moreover, in order to communicate, robots need to use communication methods that regular people can easily understand, and can be used in a face-to-face interaction. In this regard, Natural Language (NL), in conjunction with visual information is a very efficient method for an interaction paradigm with robots (see figure 1). NL-based communication is fast and successful in handling errors and uncertainties, since interaction loops with the other interlocutor make easier to reduce uncertainty and recover from errors. On the other hand, speech perception is multi-modal, it involves information from more than one sensory modality. In particular, visual information has been proven to be strongly linked to hearing when recognizing speech. This is known as the McGurk effect [8]. Moreover, it is very likely that mouth synchronization will also help in order to keep the attention of the users in what the robot says. The hypothesis of this proposal is that the HRI experience can be improved using the visual information

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provided by a robotic mouth whose motion is synchronized with the synthetic voice.

This paper presents a robotic mouth and a synchronization algorithm that can perform in real-time with different TTS systems. The robotic mouth, which is a very cost-efficient design, has been included in the Ursus social robot, a therapy robot with the shape of teddy bear. Ursus is designed in order to improve the therapy of children with developmental disorders like cerebral palsy by making a game of the therapy. Achieving an entertaining therapy for children helps them keeping their attention and improves the results.

In order to evaluate the initial hypothesis, an opinion poll was conducted with different participants, both roboticists and non-roboticists. The evaluation is based on the opinions of the participants on the synchronization algorithm and the robotic mouth regarding: 1) the impact of the different mouths used in the poll, physical a simulated ones; 2) how the different TTS systems for voice synthesis influenced user experience; and 3) the impact of the different synchronization algorithms described in the literature [9]. Other factors such as the levels of engaging, understanding or acceptance were also evaluated.

The rest of this paper is organized as follows. Section II introduces the state-of-art of the different HRI techniques and their evolution. Section III presents an overview of the proposed system. Next, the robotic mouth designed is described in section IV. Section V presents the synchronization algorithm, describing in detail the different stages of the process. Finally, the results of the experiments proposed in this paper and the conclusions are detailed in section VI and VII, respectively.

II. Related works

Affective communication has been the core topic of different social robotics works. It aims to reduce the communication gap between humans and robots not just by using natural language but also by providing robots with human-like gestures and, to some extent, shape. These techniques allow roboticists to achieve stronger human-robot empathy [10]. Moreover, humans tend to easily adapt to the interaction with agents with similar characteristics (e.g. appearance, communication mechanisms, gestures). The use of speech-guided dialogue to teach robots [11] allows roboticists and end-users to control and interact with robots using natural language. The first step to achieve this kind of interaction is to be able to send messages through media. This is done by using technologies such as audio synthesizers (TTS)[12] and speech recognition systems (ASR)[13]. These system are becoming very common in social robotics.

Robots using TTS synthesizers (e.g. [14], [15] or [16]) give rise to new systems that allow using speech to train social robots [17].

In similar works it can be found synchronization algorithms based directly on the use of audio phonemes to determine the levels of mouth aperture [18], [19]. These kind of approaches require additional information such as dictionaries of phonemes. As [20] or [21] we follow a similar approach to evaluate the different aspects of speech-based interaction.

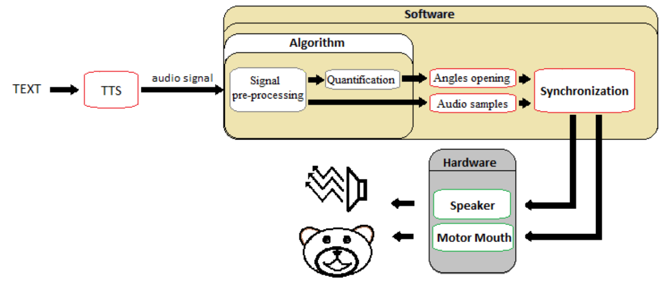

Fig. 2. Overview of the proposed system in this paper. Both, software and hardware layer are drawn in the figure.

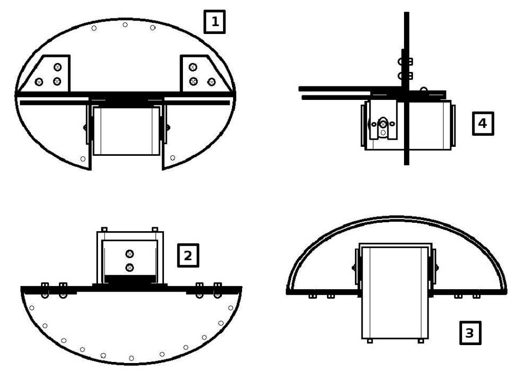

Fig. 3. Different views of the mechanical system. From left to right and from top to down: frontal, profile, top and bottom views.

III. Overview of the System

The main goal of the proposed system consists on the design and development of an algorithm to control a robotic mouth in order to behave according to the synthetic voice generated using a Text-to-Speech system. This helps keeping the attention of social robot users. Figure 2 illustrates an overview of the system. As is shown in the figure, it is constituted by two layers, hardware and software. The hardware is composed of a speaker (i.e. in order to hear the voice of the robot) and the mechanical system, which consists of a 1 degree of freedom (DOF) joint.

IV. Robotic mouth

The key design considerations for the robotic mouth proposed in this paper are: i) the efficiency of the mechanical system, considering a reasonable range of aperture of the mouth; ii) the suitability of the mouth for its use on the Ursus therapy robot and; iii) the overall price of the mouth. The CAD design is illustrated in figure 3. The mechanical structure consists on three aluminum planar pieces, corresponding to the chassis of the mouth (figure 3.1), upper and lower lips (figure 3.2 and 3. 3 respectively) and the Dynamixel RX-10 motor (figure 3.4). The upper aluminum piece is fixed, while the lower lip is moved by the motor. The mouth aperture was set up to range between 0 and 45 degrees.

Finally, the mechanical pieces are covered by a fabric similar to those used in teddy bears (figure 4).

Fig. 4. In the left hand side it can be seen the robotic mouth mounted on the Ursus 2 robot. In the right hand side it can be seen the mouth system separated from the rest of the robot, as used in section VI.

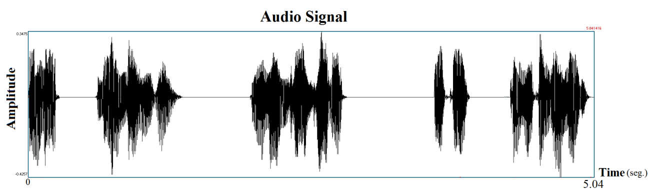

Fig. 5. This figure shows the appearance of the produced audio signal.

V. Synchronization Algorithm

A. Text To Speech System

Usually, speech synthesis systems are used so that they directly take the audio output to the speakers. In our case, since we want to make sure that the audio output is synchronized with the mouth movements, the TTS system does not have access to the speakers, it just generates the output audio file. The generated audio files are then concurrently used for producing both the mouth movements and the audio output.

Despite in section VI we use different TTS systems for comparison purposes (i.e. Verbio, Festival, Ivona and Acapela) we used Verbio[12] while developing the system and to perform the initial tests of the algorithm. Verbio can produce audio output for different languages, using various audio formats such as OGG or WAV. In particular, we use the following setup:

- Language Spanish and English.
- File format OGG.
- Sample rate $Fs = 16Khz$.

Figure 5 illustrates the audio signal obtained for the text: "Hello, my name is Ursus, tell me what is your name".

B. Signal preprocessing

As introduced, mouth movements are based on the entropy level of the audio signal. This value is calculated on-line for every time window. In order to process the signal

$$X(t) = [0, ..., F_s \cdot T - 1]$$

and obtain the entropy of the windows, the following steps must be taken previously:

- **A)** Obtain the absolute value of the audio signal:

$$V(i) = |X(t)| \tag{1}$$

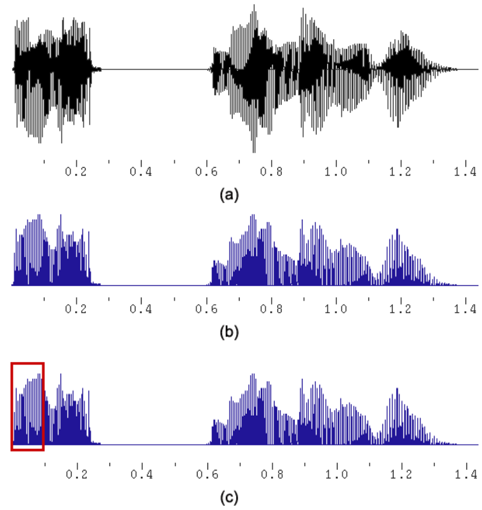

Fig. 6. Signal preprocessing: a) initial audio signal, b) absolute value of the audio signal, b) example of a time window.

- **B)** Windowize the signal vector, since the entropy is computed for each window separately.

We use time windows of a tenth of a second. The signal preprocessing step can be graphically seen in figure 6.

C. Quantification

In this work we propose an entropy-based algorithm in order to set the mouth aperture of the robot given the current audio stream. Since the audio stream is synthetic, it can be safely assumed that the audio is noise free. Thus, the algorithm provides a mouth aperture proportional to the audio entropy for each of the time windows.

Entropy quantifies the existent amount of information in a given signal, measured in bits. Given a set of different samples $1...n$ of a random variable X (which can be interpreted as a signal), the amount of information on it can be computed as:

$$H(X) = -\sum_{i=1}^{n} P(x_i) \log_2 P(x_i),$$

where x_i is the n^{th} measurement and $P(x_i)$ its corresponding probability.

Finally, the angle sent to the motor is proportional to the entropy level:

$$angle \propto entropy$$

The proportional constant was experimentally set to 1.5.

D. Synchronization

The opening levels computed by the algorithm must be synchronized with the audio sent to the speakers. This sinchronization is made using the same audio libraries which are used for playback, processing and quantification the audio signals. Thus, the audio samples are simultaneously processed by the audio library and the angles calculated in each time windows are sent to the motors of the robot mouth (see figure 2). Thus, communication delays between the computer and the motors are reduced and the synchronization results are improved.

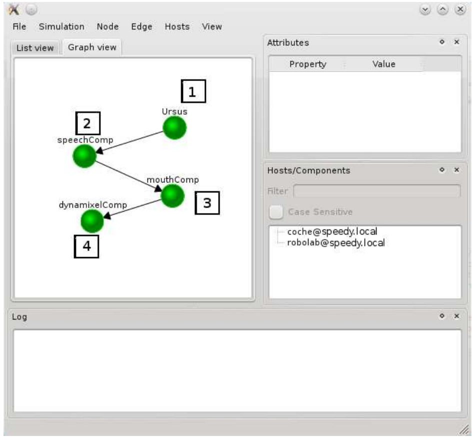

Fig. 7. Screenshot of the *RCManager RoboComp* tool. Ursus main component (1), which is connected to the TTS system (2). The component which transforms the sound in motor movements is labeled as 3. Component moving the servomotor (4).

E. RoboComp Components

The software to control our system is built on top of the robotics framework *RoboComp* [22]. Making use of the components and tools it provides and its communication middleware we developed an easy to understand and efficient architecture (see figure 7).

The main component of the proposed system is ursusComp. It is connected, directly or indirectly, to the rest of the software components controlling Ursus: camera, robotic arms, tracker, etc (figure 7). Not all components have been included in the diagram in order to make it simple. The sentences that Ursus tells its patients to encourage them during their therapy are sent to speechComp (see figure 7.2). Then speechComp transforms the sentences into sound using the specific TTS system (e.g. Festival, Verbio). After that, mouthComp (figure 7.3) receives the sound and send the motor commands using the synchronization algorithm. Finally, the motor commands are received and executed by dynamixelComp.

Since the system was designed an implemented using component oriented design/programming, these components can be easily used for other purposes, which is a very important feature in robotics development.

VI. Experimental results

One of the main goals behind the development of the robot mouth and the synchronization algorithm is to use them as an improvement for Human Robot Interaction. The initial hypothesis was that the use of a robotic mouth moving according to the synthetic voice generated by a Text-To-Speech system allows a) robots to maintain the attention of their users while talking and, b) human beings to interact more efficiently with robots. The idea is that robots equipped with motorized mouths can improve the interaction with non-expert users in human environments using a robotic mouth.

There exist different approaches to evaluate the performance of social robots when interacting with humans. In addition to evaluating the synchronization algorithm, it is also interesting and necessary to analyze how the proposed robot mouth affects humans. For this purpose, different works and researchers propose to employ quantitative measures of the human attention or body movement interaction between robots and humans. In this paper, acceptance, engaging and understanding are three factors to be measured in the HRI context. These factors are evaluated using pool-based methods, where the opinion of the user is surveyed.

Thus, the performance of the proposal has been evaluated based on the impression of the participants regarding the synchronization algorithm and the robotic mouth according to: 1) the difference in perception between a physical robotic mouth and a simulated one; 2) how the different TTS systems for voice synthesis influenced user experience; and 3) the impact of the different synchronization algorithms described in the literature [9].

Fig. 8. First version of the therapist robot Ursus.

A. Robot platform Ursus

Ursus is an assistive robot developed in the Laboratory of Robotics and Artificial Vision of the University of Extremadura (Cáceres, Spain) in collaboration with the Virgen del Rocío Hospital (Sevilla, Spain). It is designed to propose games to children with cerebral palsy in order to improve their therapy. It will also be used as a tool for their therapists to adjust therapy to the needs of the different patients. In order to make it visually pleasant for children, it has a friendly height and has been wrapped into the covering tissue of a teddy bear.

Patients can get feedback of the status of the exercise in real-time by looking at an image that the robot projects on the wall. Along with the messages the robot sends to the patients, this information encourages children to improve the execution of the exercises. Figure 8 illustrates the first version of Ursus. Ursus is composed of two arms, both of four degrees of freedom (DOF), mounted on a fixed torso. These are used so that patients can see how the robot perform the exercise and try to reproduce the movement. A regular USB camera is located in the neck of the robot to capture the arm movements of the users, allowing the robot to provide appropriate feedback about their performance. The speaker and the computer are located on the base of the robot.

B. Comparative study

Social robotics enables robots to interact with diverse groups of people, through simple and friendly means of communica-

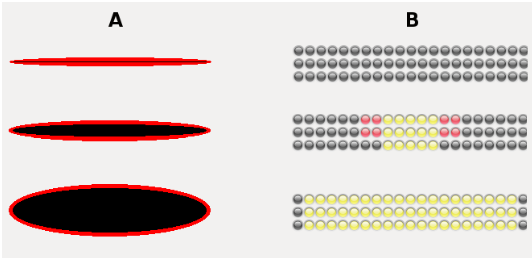

Fig. 9. Screenshot of synthetic mouths. A) Two lips mouth B) LED matrix mouth. Both are shown in three different positions.

tion such as as speech [18] [15]. A comparative survey was conducted to assess various aspects of the mouth through a series of questions with a response on a linear scale of 1-5.

The items evaluated were divided into three groups: robotic mouths, TTS software and synchronization algorithms, which were compared to determine the best in each group.

The following are the questions that the participants were asked:

- **A)** Does the mouth seem to move naturally?
- **B)** Does the mouth seem expressive?
- **C)** Did the mouth capture your attention?
- **D)** Did the mouth, directly or indirectly, help you to understand the message?

These questions were asked for every tested TTS system, and were repeated using different sentences in order to obtain an average value.

C. Comparative study of different robot mouths

The robot mouth has been compared to two different designs used for research in Human Robot Interaction. Some works are based on robots whose face is drawn in a computer model displayed on a flat screen monitor [18]. Figure 9.a illustrates the first virtual mouth used for the experiments. It consist of two lips that are moved according to the proposed synchronization algorithm. The second robotic mouth included in this comparative study is based on other research works that use a LED matrix [9] (see figure 9.b). Instead of developing the hardware LED matrix, it was also simulated in a computer screen. It consist of a 21x3 matrix whose elements are enabled according to the synchronization algorithm. The color of the elements depends on the entropy level (yellow for high, red for medium and gray for low level, respectively). Both mouths are displayed on the screen monitor using a size similar to the one of Ursus. In figure 4 it is shown the set up used for evaluating the robotic mouth.

The same pool and participants were used for evaluating the features of the different robotic mouths. Results are summarized in table I. As shown in table I, the robot mouth presented in this paper performs better compared with other mouths. It got more interaction and attention levels from the participants.

Mouth	Questions			
	A	B	C	D
Animated mouth	72%	72%	62%	68%
Led mouth	38%	40%	44%	50%
Robotic mouth	74%	66%	74%	64%

TABLE I
COMPARISON OF THE DIFFERENT MOUTH

D. Comparative study of the different Text-To-Speech systems

This section describes the evaluation of the different TTS systems considered. In this study we used four different TTS systems: Verbio, by Verbio Technologies; Festival, by the University of Edinburg; Acapela, by the Group Acapela; and Ivona, by the company Ivona Software.

One of the main aspects to take into account when using a TTS system is the output sample rate. In this study, for each TTS, the following sample rates were used.

- Verbio: $16Khz$
- Festival: $44Khz$
- Ivona: $22Khz$
- Acapela: $22Khz$

The algorithm can be used with any TTS system, as long as it complies with certain parameters such as audio sampling frequency or the ability to produce output files.

For the evaluation of the TTS systems we used the questions specified in section VI-B. The evaluation results of the TTS systems are summed up in table II.

TTS	Questions			
	A	B	C	D
Verbio	52%	46%	52%	72%
Festival	60%	56%	52%	80%
Acapela	68%	72%	68%	72%
Ivona	64%	60%	56%	68%

TABLE II
COMPARISON OF THE DIFFERENT TTS

The results seen in the table, show that the Acapela TTS software performs better than other TTS in aspects such as naturalness or expressiveness. In addition to evaluating the synthesizer, the poll took into consideration the performance of each TTS with the different mouths. The corresponding results are shown in table III.

TTS/Robotic mouth	Questions			
	A	B	C	D
Verbio	74%	66%	74%	64%
Festival	50%	45%	50%	60%
Acapela	80%	75%	80%	70%
Ivona	65%	60%	70%	60%

TABLE III
COMPARISON OF THE DIFFERENT TTS IN THE ALGORITHMS OF SYNCHRONIZATION

Table III shows that the best achieved performance is produced by Acapela in conjunction with our synchronization algorithm and the robotic mouth developed for this paper.

E. Comparative study of different synchronization Algorithms

Finally, the comparative study allowed to evaluate the synchronization algorithm compared to other algorithms, such a binary pulse delivery aperture (mouth opened if there is sound) and other that controls movement through random levels of mouth aperture.

For the evaluation of these synchronization algorithms a survey was made with the questions of the subsection VI-B. Results are summarized in table IV.

Algorithms synchronization	Questions			
	A	B	C	D
Entropy	80%	80%	80%	64%
Random	40%	44%	40%	36%
Binary	48%	44%	48%	48%

TABLE IV
COMPARISON OF THE DIFFERENT TTS IN THE ALGORITHM OF SYNCHRONIZATION

The results of the survey demonstrate that the synchronization algorithm based on entropy provides a better user experience. Besides being the best performing algorithm in speech perception, it has other features that make it useful for social robotics, as its ability to work with any TTS software.

VII. CONCLUSION AND FUTURE WORKS

Social robots need to communicate to improve their level of interaction with people. Visual and auditory sources must be taken into account as demonstrated by McGurck[8]. The use of visual feedback can be used, not only to improve understanding, but also to achieve higher levels of attention and empathy.

The results provided by the survey demonstrate that the proposed algorithm is better than most state-of-the-art algorithms. Moreover, our algorithm performs in real-time and does not require additional training such as other approaches[18], [19].

We are currently working in order to be able not only to provide speech information to the user but also to receive it. By removing the need to make the user move (i.e. in order to touch a touchscreen or make a gesture), we expect that user experience will be dramatically enhanced.

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