PhD in Information Technology and Electrical Engineering

Università degli Studi di Napoli Federico II

PhD Student: Carmela Calabrese

XXXIII Cycle

Training and Research Activities Report – Third Year

Tutor: Mario di Bernardo – co-Tutor: Benoit Bardy

1. Information

Carmela Calabrese, MSc in Ingegneria dell'Automazione – University of Naples Federico II
XXXIII Cycle – joint PhD programme between the University of Naples- Federico II and University of Montpellier (VINCI fellowship)
Tutored by Professor Mario di Bernardo and Professor Benoit Bardy

2. Credits summary

	Credits year 3							
		1	2	3	4	5	6	
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	**Summary**
Modules	3	3	0	4	0	0	0	**7**
Seminars	1	0.2	0	0	0	0	0	**0.2**
Research	60	6.8	10	6	10	10	10	**52.8**
	64	10	10	10	10	10	10	**60**

3. Study and training activities

- Attended courses:
  - Game theory and analysis of competitive dynamics for industrial systems— Lina Mallozzi
  - Design and implementation of Augmented Reality Software Systems— Domenico Amalfitano

- Attended seminars:
  - Additive Manufacturing: modeling and computational challenges

- External courses: none

4. Research activity

Title: Analysis of synchronization and leadership emergence in human group interaction.

Understanding how and why human beings gather and interact in groups to accomplish and satisfy deep instincts and primary needs are key research questions across different scientific disciplines, from neuroscience to engineering. Answering these paramount questions is challenging as interpersonal cooperation involves different levels of interactions, it occurs across diverse social contexts and relates to different types of individuals with various knowledge, skills, and abilities. Specifically, perceptual-motor synchronization in human groups is a common phenomenon which is crucial to enhance performance in musical ensembles, dancers' crews, or team sports. In the literature, the investigations on group interactions with a finite number of members (N = 5 - 7 people)- differently from dyadic cooperation and crowds- is much less studied and the results are rarely formalized through a mathematical framework.

A part of the third year research has been devoted to investigate the neuroscientific mechanisms underlying the group motor interaction.

Cognitive responses during human group interaction can be explained both in terms of the so-called *theory of mind* and as the motor responses driven by the sensory feedbacks of the interaction. However, while human interactions have been systematically investigated over the last decades across different fields, the contributions of the cognitive and motor responses to human group coordination are only partially understood.

Networks of heterogeneous Kuramoto oscillators have been successfully employed to explain how synchronization may emerge in human groups performing oscillatory tasks. However, this model predicts synchronization to the average frequency of the individual characteristic frequencies, which is in contrast with our experimental observation that, when synchronizing, the group tends to consistently reduce their average frequency. These experimental findings are in agreement with previous observations in the joint-action literature. For instance, inhibition of the motor output pathway has been extensively studied in the context of action stopping, where a planned movement needs to be abruptly stopped, jointly or alone. These works explain how the brain selects actions, regulates movement initiation and execution, showing that joint action requires a more selective and slower mechanism compared to individual movements. This phenomenon has been observed across diverse tasks and applications, including in tapping experiments, where researchers found that participants tapped faster alone than when they are involved in cooperative tasks, or in human-robot interactions. The significantly large temporal difference between interacting partners is necessary to gain time to see what the other person does during joint interaction. By slowing down, resources could be freed-up and the own and the other's movement could be judged.

Within the context of the mirror game, we propose three alternative modifications of the traditional Kuramoto model to explain the observed reduction in the synchronization frequency of the group. In particular, the three alternative models are grounded on three main neuroscientific hypotheses. We found that a model accounting for delays in information processing is the one that best captures the reduced frequency of oscillation observed in our experiments when compared to solo trials. In fact, the sensorimotor control system requires coordinating different forms of sensory and motor data and these data are generally in various *formats*. Transformations between these coordinate systems allow the motor and sensory data to be related, closing the sensorimotor loop. Therefore, to generate skilled actions, the sensorimotor control system must find solutions to several problems, including coping with the nonlinear nature of our motor system, together with delays, redundancy, and noise.

Neural delay has been shown to play a significant role in the muscle control system. This delay can be defined as the total time interval between the presentation of a stimulus and the evocation of a response. It can be influenced by the length of the neural path between the receptor organ and the responding muscles, the time that the central nervous system requires to process the information, and the time it takes for a muscle to react. For this reason, four sequential components play a key role in the neural delay: sensation, perception, conduction, and execution. These delays combine to give an unavoidable feedback delay within the negative feedback control loop, which ranges between about 30 ms for a spinal reflex up to 200–300 ms for a visually guided response. Tuning our simple yet effective model, which explictly accounts for these intrinsic delays, we found delay values that are in line with the typical range evidenced in the literature, and specifically between 110ms and 310ms.

The second part of the third year has been devoted to the preliminary investigation on the effect of virtual players that can influence and steer the overall group dynamics towards a certain level of coordination.

Researchers in Social Neuroscience proposed the use of a new interaction paradigm termed as Human Dynamic Clamp (HDC). Inspired by the neuronal dynamic clamp, the HDC allows to directly manipulate in real time the interaction or coupling between a human and an avatar constructed to behave like a human, driven by well-established models of coordination dynamics. This novel interaction paradigm allows to explore a wide repertoire of human behavior and shed light on those features that cannot be easily accessed in standard human interactions. In our work, inspired by the human dynamic clamp paradigm, we used our hardware-software platform *Chronos* to include artificial agents in a group of humans performing a joint motor task to analyse how they influenced the emergence of human coordination. Indeed, several behaviours and hypotheses can be explored and investigated on human group coordination by varying the mathematical model of the artificial agent and playing with its parameters. Experiments showed that the addition of a VP to the group changes the collective dynamics significantly. Our preliminary results also show that the leadership patterns emerging from the interaction are affected by the presence of the VP. The investigation of these and other observations are left for future work.

The results presented in this Thesis can be instrumental in a number of different applications. First and foremost, the results we presented can be crucial in developing avatars and virtual players for the rehabilitation of patients suffering from social disorders, such as schizophrenia or autism. Autism affects about 1% of the adult population with very high associated costs. Deficits in social interaction, typically diagnosed during conversations, are the most significant and the most difficult deficits to rehabilitate for an autistic patient. Differently from traditional therapies, the final goal of this project is the development of a new software platform for group tele-rehabilitation able to assist medical staff and minimize distances, time and costs. Our approach is also relevant for robotics, where mathematical models and control algorithms are needed for robots to cooperate with humans in a safe manner, and in human-machine interaction to perform challenging tasks, for example in logistics or in risky environments.

5. Products

- Journal papers:
  - [in preparation] **Calabrese C.**, De Lellis P., Bardy B.G., di Bernardo M.- Capturing human slowing down during group interaction: modified Kuramoto models.
  - [submitted] **Calabrese C.**, Lombardi M., Bollt E., De Lellis P., Bardy B.G., di Bernardo M.- Self-emerging leadership patterns facilitate the onset of coordinated motion in human groups- submitted
  - Bardy B.G.*, **Calabrese C.***, De Lellis P., Bourgeaud S., Colomer C., Pla S., di Bernardo M.- Moving in unison after perceptual interruption- *Scientific Reports*, 10(1), 1-13, 2020.
  - Della Rossa F.*, Salzano D.*, Di Meglio A.*, De Lellis F.*, Coraggio M., **Calabrese C.**, Guarino A., Cardona-Rivera R., De Lellis P., Liuzza D., Lo Iudice F., Russo G., di Bernardo M.- A network model of Italy shows that intermittent regional strategies can alleviate the COVID-19 epidemic- *Nature communications*, 11(1), 1-9, 2020.

* These authors equally contributed to this work.

- Conference papers: None

6. Conferences and seminars

- Program Committee member of the Ninth edition of the International Conference on Complex Networks and their Applications (Complex Networks 2020)
- Weekly participation to internal lab meetings (2 hours) of SINCRO group research.

7. Activity abroad

- Short-term research period at EuroMov Centre, University of Montpellier —from 01/09/2020 to 31/10/2020.

8. Tutorship and teaching assistance

- Teaching assistance:
  - 2 hours in the course course “Identification and Optimal Control” in Ingegneria dell’Automazione (magistrale).
- Tutorship:
  - Weekly 2 hours tutorship (“ricevimento”) for the course of Dinamica e Controllo Non Lineare in Ingegneria dell’Automazione (magistrale), and the course of Controlli Automatici in Ingegneria Informatica (triennale).

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	Credits year 1							
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary
Modules	15	0	0	6	5	0	3.4	14
Seminars	6	1.6	1.6	3	0.2	0.2	0.2	6.4
Research	40	8.4	8.4	1	4.8	9.8	6.4	39
	61	10	10	10	10	10	10	60

	Credits year 2							
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary
Modules	12	5	0	5.2	0	0	0	10
Seminars	3	0	0.4	2.6	1.4	0	0	4.4
Research	40	5	9.6	2.2	8.6	10	10	45
	55	10	10	10	10	10	10	60

	Credits year 3									
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Total	Check
Modules	3	3	0	4	0	0	0	7	32	30-70
Seminars	1	0.2	0	0	0	0	0	0.2	11	10-30
Research	60	6.8	10	6	10	10	10	53	137	80-140
	64	10	10	10	10	10	10	60	180	180