Definitions and Metrics for Social Robotics, along with some Experience Gained in this Domain

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***Abstract*—Social robotics is currently a field of strong interest for at least two reasons: the emerging possibility to have robots helping humans; and the conjecture in evolutionary biology that humans have seen their cognitive capabilities and their unique brain properties develop out of social requirements. The paper discusses these contexts, shows the continuity through scale changes, namely at collective, nominal and subsystems levels, of cognitive concepts and processes. On this basis, what has been introduced for individual cognitive agents, including evaluating techniques, is mapped onto societies. Among other aspects, individual meditation and thinking are shown to become social deliberation and discussing. Examples with a robot group helping humans in domestic and restaurant applications are also developed and discussed.**

Keywords—cognition; social deliberation; cooperative robotics; formal definitions; quantitative assessment; psychometrics; cognitive metrics; evaluation.

I. Introduction

For centuries and more, humans have tried to develop artificial means capable of serving them, or entertaining them, with various degrees of success. Initially realized with tools, techniques were added when language and writing systems have allowed. Only in recent decades could artificial cognitive agents be added to this series of resources.

Cognition deserves attention in many ways. Of interest here are particularly the attempts to develop artificial cognitive systems; the study of evolutionary biology as a source of inspiration to better understand human cognitive properties; and formal definitions and metrics as means to quantitatively assess and compare cognitive properties.

Bruno Siciliano [1] is a good example of authors who have underlined both the efforts to have an artificial system "cloning" humans, and also the endeavor of developing machines functionally useful to replace workers (e.g. Rapperswil).

Ralph Adolphs [2], provides an interesting review on research done in connecting social cognition requirements and the developmental evolution of human brain.

Appropriate formal bases and a metric system for cognition, applicable to humans as well as to artificial implementations have been proposed and successfully tested [3].

But the three kinds of contributions just mentioned are still quite isolated from one another, even though some works are also underway addressing a sociology of robots [e.g. 4, 5, and enclosed references]. It is now time to bring them together and relate them for more mutual benefits; this is the reason for some of our activities, which we report with updates in the current paper.

The paper is organized as follows. Section II sets-up the context and thus summarizes the main relevant aspects of the state of the art. Section III introduces new formal definitions and metric elements for an ontology of social robotics. And finally Section IV illustrates with concrete examples the concepts introduced in the previous section.

II. Setting-up the Context

Let's briefly review the state of the art for the three main components referenced in the introduction: "cloning" humans, fulfilling social requirements for intelligence, and bringing a formal basis for quantitative, scientific and technical approaches to cognition.

A. "Cloning" humans

In the quest for human clones, difficulties encountered are very different depending on the nature of equivalence sought, essential or functional.

In the first, essential sense, cloning is quite impossible as humans are really social animals, with important cultural features; even if ultimately at physical level bioengineering techniques for cloning would be somehow successful, which is still a challenge, the part of personality acquired through education, learning and experience, for decades, would still seem rather impossible to replicate at any significant level of relevance.

In the second, functional sense, chances are much better, and in fact the revolution is already well underway. For example today many electronic banking outlets allow customers to perform basic transactions on their own and the assistance of branch employees is no longer required (re. Automatic Teller Machines). The challenge we focus here is the implementation of automated cognition.

In this effort, consider the analogy of technical transports: researchers and engineers did not really study the human legs

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to invent the wheel, trucks, trains, boats, jet planes or space shuttles. Similarly today the study and replication of the human brain may not be the necessary road to automated cognition and social robots.

In the world of cognition, researchers have first focused of the concept of intelligence; and in this respect, notice that according to the most established definition, the one of Alan Turing, intelligence is recognized purely in behavioral terms, on the basis of information exchanges that do not imply any specific structure nor physical implementation.

B. Large human brain for social cognition requirements?

Whether or not social cognition requirements have been causal for the growing, evolutionary size of human brain, they remain critical today for the widespread use of social robots.

An important part of the research community conjectures that the ecological niche of humans, and in particular their nomad life style, has set high constraints on their survival condition. These constraints could only be met by a collective organization, a group, and therefore in turn they have set very challenging requirements on human individuals in terms of social cognition capabilities. The core idea is that such an evolution could not have happened in our species lifetime without an adequate, simultaneous development of human brain.

Dunbar is particularly representative of this conjecture [6]. His work has shown that group coordination implies a significant effort in mutual grooming of group members, which increases as a function of group size. He has notably established by comparison with non-human primates that the human brain should typically allow humans to keep stable social connections with up to 150 people.

There are however also other views. Miller [7] has developed a conviction that the main drive for the development of human cognition has been the sexual choice to operate for appropriate gene selection, which remains well compatible with Darwin findings. Far from the theory of a necessary large brain, there is ample evidence that complex scenarios can develop for species survival without much development of cognition, as numerous cases of parasitic life cycles demonstrate [8]. And this sometimes includes induction of unwitting behavioral changes of host organisms. Flegr has reported on the case of intracellular, parasitic protozoans causing disease in animals, including humans, and in the latter case even affecting subtle cognitive capabilities as well as sexual selection of subsequent generations [9].

From an engineering perspective, the priority at this point is to identify critical requirements in social robots; and then of course the allocation of resources to meet them should follow for successful implementation.

C. Formal bases and metric system for cognition

In cognition like for physical phenomena, the possibility to perform rigorous quantitative estimations is quite mandatory for fostering progress.

So far however this has usually been done in ad hoc ways, where the nature of the application field is deeply intertwined with the purely cognitive component.

For example in chess games, cognitive skill levels are expressed in Elo units; for tennis, the ATP (Association of Tennis Professionals) manages points in a similar way. In the case of Dunbar above, cognition levels are characterized in particular by kilograms of brain weight, and/or a number of connected group members.

Specific formal bases and a metric system for cognition, *generally applicable to humans as well as to artificial implementations* have been proposed and successfully tested, in the context of the MCS (Model for Cognitive Systems) cognition theory [3].

The careful observer can identify two critical hinges between traditional definitions and the corresponding novel, axiomatic definitions in MCS theory: the concept of information, along with the notion of time.

Thus cognition is the capability to generate relevant information, possibly as a function of some other, incoming information. Typically, the delivered information is not explicitly (pre-) stored in memory but on the contrary is freshly cranked out on request, by an engine with knowledge (re. Fig. 1).

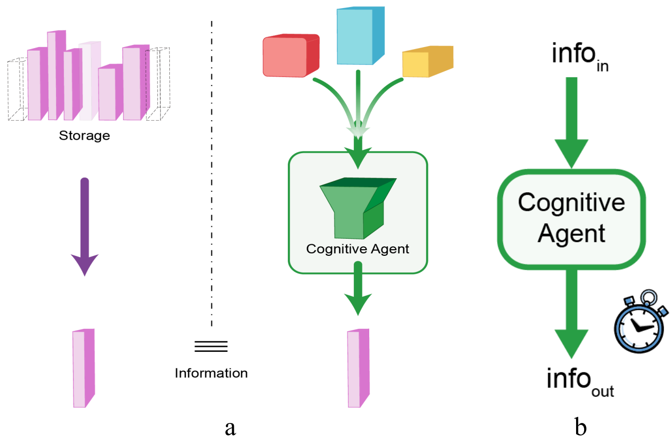

Fig. 1. Schematic view of cognition. *a*: Cognition and, effectively, cognitive systems (re. text). *b*: Cognitive properties can be quantitatively estimated on the basis of input-output information flows, and time (re. text).

As usual, information is typically measured here in “bit” units, and time in seconds. From values of this type, according to MCS theory for cognition, knowledge quantities can be measured in “lin” units, expertise in “lin/s”, experience in two alternate ways, seconds or bits, depending on the degree of sophistication selected for modeling. Limiting the current review to the most central entities, the last property here to consider is intelligence, which is defined as the derivative of expertise with respect to experience.

In particular, knowledge, K, is a function of input and output information quantities, n_{in} and n_{out} (re. Fig. 1):

$$K = \log_2\left(n_{out} \cdot 2^{n_{in}} + 1\right) \quad \text{[lin]}$$

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Notice that defined as just presented, the field of cognition inherits not only the favorable aspects of the classical concept of information (theory, measuring units, etc.) but also the unavoidable, strong limitations associated with it: time dependence, subjectivity, and above all, the necessary, tight confinement in some kind of model (by nature, very abstract and simplified with respect to the corresponding *domain* of reality; yet usually effective for some selected goals).

In MCS theory, the core concepts are typically defined in a way compatible with the usual, general understanding. Nevertheless if the user wants to explicitly refer to the rigorous, axiomatic definitions provided in this ontology, it is proposed to add-up a "c" as a prefix; e.g. : c-speed, estimated in [1/s] units.

If the reader still doubts about the equal applicability of these MCS definitions both for humans and machines, consider as a supplementary argument the classical Turing test for intelligence: there also, it is essentially the flow of exchanged information that supports the judgment of experts; and time properties have there also an influence on appreciations.

D. MCS cognitive metrics and classical psychometrics in social cognition

The metric system presented above in Section C already overlaps in two ways with classical approaches in psychometrics applied to social cognition: domain peculiarities, and similar semantics, for sometimes-different words. Moreover, when now considering social robotics, MCS deserves new extensions as will be introduced in the sequel, in Section III. But let us first briefly reference classical works in psychometrics and social intelligence, both for humans, and later on, for digital contexts.

1) Classical psychometrics and social intelligence: Even though the place is short here, we cannot go without mentionning some valuable works made in reference to the social abilities of humans (e.g. classically with Thorndike, Guilford, O'Sullivan, or Gardner [10], or through their later influence in robot and computer-human interactions [11-14]).

2) Overlap of domain-related notions: The first overlap between MCS and classical psychometrics relates to the domain of reality that is under consideration. From MCS perspective a domain is a domain. To say more about this domain relates not to MCS theory itself but rather to its contingent application. As an example, consider information, knowledge or expertise, like length or permanence: all these properties are defined and quantized in exactly the same way (re standard units: bit, lin, lin/s, meter or second), no matter whether they relate to tennis, to chess, to arithmetic calculus or yet to a particular social behavior. In this sense, there is a full compatibility.

3) Semantic similarities: The second overlap between MCS and classical psychometrics relates to core cognitive notions. If carefully tracked, the notions behind different apparent names and definitions may well often be the same. For example information may in one case be metric and in the other framework be only quantitative; a common difference in historical definitions may be expertise for MCS versus intelligence in psychometrics. The lack of rigorous definitions in classical psychometrics may well explain why IQ (re. cognition) sometimes is used as estimate for social expertise (a domain-related property) in classical studies. In MCS, the metrics provided for abstraction and concretization could quite directly apply to the notions of cognitive convergence and divergence, which are classically estimated in a rather qualitative manner and could thus be conveniently measured.

III. Ontology Components in Social Robotics

Moving from general cognition to social robotics, two aspects need first additional, specific considerations: the social nature and the robotic essence; then in the third subsection, a special attention is shed to their overlap. Moreover, the current conference introduces another notion, "evaluation", which deserves its own discussion; this is done below, in the fourth subsection.

A. Social nature

The social attribute has at least two different meanings, which are worth discriminating: the first one discussed here relates to a friendly companionship; the second one is deeper and more generally refers to all relationships founding the collective character of structures gathering multiple individuals.

1) Social, as a friendly companion: In the context of the current conference, the social attribute mainly refers to services that robots can give to humans. Essentially, the word is here a synonym of "cooperating with humans".

In this sense there should be a priority in focusing on elements referring to human-robot interaction, or as sometimes also considered, human-agent interaction.

This definition is more restrictive than the fundamental definition given next, and therefore it is worth addressing the latter in more details.

2) Social, essentially as members integrated in a group: Fundamentally the social character of an agent essentially denotes its (successful) integration in a collective structure, a group.

In this sense, for an individual (human, animal, robot or another cognitive agent) to be social, somehow there must be a certain number of other individuals and some connection between them. This is sufficient to define a "c-group" (re. Fig. 2).

Notice that according to the fundamental definition, the requirements to be social include an adherence with the specific culture of the group; ultimately, such an attitude deserves the "friendly companion" attribute discussed above, in paragraph A.

In terms of quantitative evaluation, all the entities and metric formulas defined for a cognitive system (knowledge, expertise, learning, intelligence, etc.) are directly applicable for the social aspects as well. The *social* attribute relates not essentially to the core cognitive faculties but rather to the application *domain* only. Thus in any social domain considered (e.g. politeness in greeting or kindness in giving the way) evaluation must be done, like for any other cognitive domain, of the amounts of information conveyed, both in the input and correct output flows of the CA, as the latter operates.

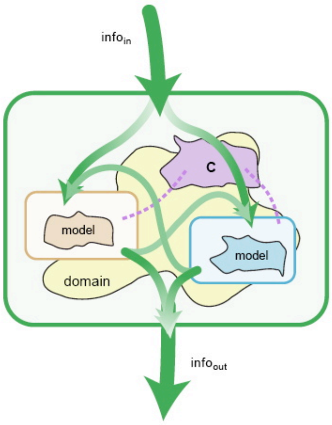

Fig. 2. At an individual scale, singular agents (brown, and blue boxes) update their own models, according to the pieces of information they have received. Together, as they share common elements, C (like Culture), they implicitly build-up a group, which globally can also be viewed as a new, single cognitive agent.

In terms of quantitative evaluation, all the entities and metric formulas defined for a single cognitive system are identically applicable at group level as well. The social attribute relates not to the core cognitive faculties but to the application domain only. Thus in any social domain considered (e.g. politeness in greeting or kindness in giving the way) evaluation must be done, like for any other cognitive domain, of the amounts of information conveyed, both in the input and correct output flows of the group, as the latter operates.

B. *Robotic essence*

What is a robot? Four elements of answer may be useful here.

From etymology considerations, a robot is a "working" agent, implicitly operating for the benefit of humans.

In the real-world, a robot is primarily "motion": a mechanical structure, with sophisticated kinematic and dynamic skills, capable of exerting forces and torques, for body and arm motions in space, as well as for grasping and transporting objects.

From a cognitive point of view, a robot is usually seen as featuring five main capabilities; three core faculties, perception, decision, and action, along with two ancillary abilities, locomotion and communication.

And finally, in a very unique way, robots have the extraordinary power of relating the abstract, model-related, immaterial, cognitive world on one side, with the infinitely complex, physical, real world on the other side; in real-time; interactively (e.g. Fig. 3).

Now what about quantitative estimation? Each of the four elements given above may be considered in its specific way:

- As a working agent, a robot can be quantified like a human worker.
- As a resource for motions, a robot can be rated with all the traditional physical units, such as force in [Newton], acceleration in [m/s2], angles and angular accuracy in degrees, etc.
- According to element 3, the MCS set of metric formulas apply
- In case 4, both the cognitive and the physical entities can be quantitatively estimated, with a particular role played by the notions of power and energy.

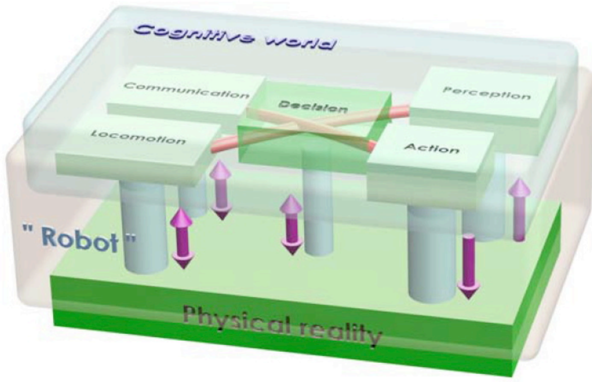

Fig. 3. Schematic view of a robot, modeled as featuring 5 essential cognitive capabilities, embodied in a material structure for the purposes of grounding and deployment in the real-world. Internal information flows are shown in red, and energy in purple color.

C. *Overlap – degrees and modes of cooperation*

Social robotics, in the sense of current conference, draws particular attention to a conceptual area where elements of two different integration levels overlap in cognitive systems: the individual: and the group this individual is associated with (e.g.. Fig. 4).

Key questions that arise in such a context include the degree of mutual cooperation, as well as decisions to change such types of cooperation.

In a first approximation, we suggest to define four states of possible cooperation between an individual cognitive agent and a group under consideration.

- Associate. The first, and in principle maximal, cooperation level is the one of membership: the individual *is* (part of) the very essence of the group; conversely, the group consists in the association of this member and typically multiple other ones.
- Friendly. Friendly is defined here as the attribute of a cooperation that has positive effects, that is c-good, i.e. helping in attaining a goal. It could be viewed as a positive kind of cooperation.

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- Neutral. Neutral is defined here as the attribute of a relation that has no effective outcome. It could be viewed as a nil level of cooperation.

- Hostile. Hostile is defined here as the attribute of a relation that has negative effects, that is c-bad, i.e. reduces the capability of attaining a goal. It could be viewed as a negative kind of cooperation.

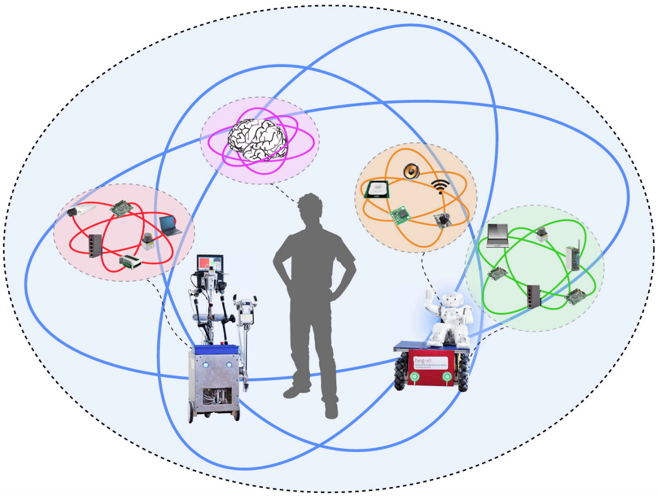

Fig. 4. Five examples of collective cognitive systems, at two scale levels: within overall, social group (blue color), and within 4 individual agents: a human, and three robots, including a humanoid (red, magenta, orange and green colors) . In the case of the human, only the mental network of cognitive subsystems is represented.

Depending on the levels of cooperation that are experienced and evaluated (re. next paragraph, D), changes may happen in terms of cooperation modes: in the case of membership in a group, choices include adherence and resignation from the member point of view, and some kind of registration and dismissal from the group point of view. More general types of change include entering or quitting cooperation.

As it is shown in Fig. 4, interactions may often occur with multiple groups. In particular an interesting analogy could be drawn between different levels of integration: internal deliberations among subsystems of the human brain are denoted “thinking”, yet they are not essentially different from deliberations made at the higher level, i.e. between individuals, human or robot, within the common group. It appears from this property that some mapping could be more systematically explored between psychology and sociology theories (Consciousness, emotions, hypnosis, mental blocks, repression, unawareness).

D. Evaluation

In general, evaluation can be performed by taking into account two very different kinds of contributions. One is objective, quantitative, and factual. The other one is subjective, and refers to the perceived utility of potential users.

While scientific approaches usually address issues in natural and technical realms, which is appropriate for the first type of contributions just mentioned, the concept of value also includes aspects pertaining more to social psychology and economy, i.e. relates to the second type of contributions.

Let us successively comment both types of contributions, and then application will be made to the case of evaluating social robots.

- Quantitative contributions. For the first type of contributions, all the physical units may be appropriate (e.g. kg of rice, minutes of medical service, etc.). In the non-physical world, information is also well served by a metric system (re. [bit] unit) and for cognitive entities, the MCS metric system presented above are of upmost value.

- Subjective utility. In the process of evaluation, the concept of value is of course central. Value is also quite central in the economic realm, and relates to the second type of contributions mentioned above. Classically in economic context, value levels are easily expressed in monetary terms. For commodities, i.e. goods or services available in large quantities, the value is automatically assessed by the market, as an equilibrium between supply and demand. For cases where objects or services are rather unique, values are highly subjective, volatile, and assessment necessarily remains uncertain. For cases where no market develops, as for general situations in economy, questionnaire-based enquiries and interviews are typically performed with potential target users in order to estimate the value of planned new products and services. Another class of solutions for evaluating objects and services, when no market data exist, relies on Delphi studies, i.e. the opinion of specialists.

- In the case of evaluating social robots, the same principles apply: more quantities mean more value; and more common objects or services (i.e. commodities) mean a better-established value by the market. In the realm of cognition though, complexity levels are generally so high that heterogeneity is more the rule, and therefore the subjective components tend to play a large role. Consider the extreme case of art: uniqueness often applies, which translates into very high uncertainty on value levels.

IV. SOCIAL ROBOTICS IN ROBOCUP@HOME COMPETITIONS – TWO REPRESENTATIVE CASES

Social topics largely involve cognitive aspects. And cognition (re. “AI”) is a critical component, along with robotic structures, of the international Robocup initiative [15]. Robocup very much addresses soccer problems, but other themes are also present. In particular, the Robocup@Home league explores social robotics possibilities in domestic environment. That is why two applications have been selected in Robocup-at-Home context, in order to illustrate above concepts in the real world.

After successively presenting below an abstract of both applications, a third section focuses on the evaluation of their performance.

A. Serving a drink and snacks at home

For the Robocup@Home world competition in Singapore, the RG-Y group of robots of Fig.4 was in particular engaged in a test where some social robotics capabilities could be successfully performed and rated.

The main robot for grasping and transporting objects was RH-Y, complemented with a second arm, of Katana type; the humanoid platform NAO, of Aldebaran Robotics, was integrated in the group for its good capability of mediating between humans and other machines; finally, the robotic platform OP-Y could ensure reliable and safe motions of NAO at home, moving over carpets or passing doorsteps. (A similar application has also been made in our lab, where essentially affiliation logos of internship students had replaced the original food and drink elements).

B. Social robot as a restaurant waiter

A current test, designed for the Robocup@Home competition 2014 in Brazil, consists for a robot (or a robot group) to take over a typical social task in a restaurant as follows: to receive guests with a friendly and personalized service, consisting in taking orders for drinks and food, fetching the latter and delivering it on their tables.

Fig. 5 presents a view of the order form designed for this application, in our proprietary Piaget environment for programming and real-time control.

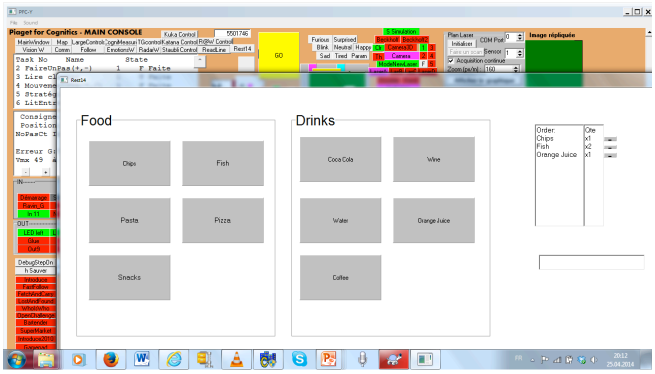

Fig. 5. Example of robot RH-Y form for interactively taking orders in a restaurant. Orders may be taken with a tactile screen or given vocally.

C. Evaluating performance

As shown in Section III.D above, evaluation includes objective, as well as subjective elements. Let us practice here an evaluation for both types of contributions.

In the first case, a quantitative estimation of knowledge and expertise is performed for the case presented above of a robot at home. In the second case, subjective elements will be shown for the case of the robot performing as a restaurant waiter.

Robots serving "at home". Consider for this case some selected, representative cognitive capabilities.

As a general rule, and according to the current best practices in computer programming, we typically focus as narrowly as possible on the requirements of the rulebook.

The general start signal is given by a physical button (1 bit). The coordination signal between robots is conceptually exchanged by Wi-Fi. In practice this can also be done with a distance sensor. Considering that 1 bit of information is extracted in a minimal model - fixed angle, fixed distance threshold, on the basis of 784 x 12 bit of incoming information at sensor level, the perceptive knowledge is therefore here of about 9'408 [lin]. And with a reaction time of 0.1 s, the amount of expertise is about 94'000 [lin/s].

Robot as a restaurant waiter. In the second example, evaluation also does include both objective, and subjective elements. Let us though focus here on the latter type.

It appears that evaluation is here very much performed according to the Delphi principle mentioned above.

For ranking purpose in the competition, the technical committee, like for chess or tennis for example, have established an ad hoc score sheet (re. Table I and [16]).

TABLE I. SCORE SHEET - RESTAURANT

The maximum time for this test is *10 minutes*.

Action	Score
Guide Phase	
Reaching a *location* in the guide phase	*5 × 50*
Navigation Phase	
Reaching a (task-relevant) *location* in the manipulation phase	*4 × 100*
Grasping the correct objects	
Successfully grasping a correct object from a shelf	*3 × 250*
If object was grasped from a low or high shelf	*3 × 200*
Delivering the correct objects	
Successfully delivering the correct object to the correct location	*3 × 200*
Special penalties & bonuses	
Not attending (see sec. 3.7.1)	*-500*
Outstanding performance (see sec. 3.7.3)	*260*
Total score (excluding penalties and bonuses)	*2600*

As can be seen in the table, a quantitative value (here denoted "score") is allotted to about 10 different elements.

The subjective opinion of experts is taken into account here schematically in three ways, as follows:

- *Test definition*. The very first step is the definition of tests. The idea is to have the most representative tasks for a robot helpful in domestic domain, in a progressive way. This is already de facto a certificate of value.
- *Score definition*. A second step in the elaboration of the rulebook is the definition of scores. The purpose of stating an explicit value is here as much in order to steer efforts towards priority R&D goals as to recognize possible a posteriori success.
- *Bonus*. A possible a priori unidentified bonus is also present on the score sheet, in anticipation of possible worthwhile, novel performances.

Notice that in some other tests (actually also for the previous case in Singapore) an evaluation is also made on a Delphi basis, but instead of the technical committee, the evaluating specialists are here the peers, i.e. the leaders of all other teams. This is especially useful for unique cases, for which no relevant scoring criteria can a priori be elaborated.

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This paper has a kind of constructivist approach, whereby foundations are first set into place. Now for readers who are not familiar with the field, it may be worth mentioning that other works have been done, where *domains* more typical of humans are also considered by robots: have therefore for example a glance to the case of robots and emotions (e.g. [17] and references in it).

Notice that the same metric approach illustrated above could also be concretely applied for the "Who is who" test of Robocup@Home, which quite exactly matches the "*Memory for Names and Faces »* criterion of the classical psychometric George Washington Social Intelligence Test (e.g. [10]).

Similarly, in principle all human situations could be rigorously assessed with the proposed metric methodology, either directly for human agents or for their machine-based alternatives.

In practice however, the most serious limits for deployment of artificial cognitive agents may stem from the fact that they do not share a similar experience of life (eating, going to school, reading newspaper, riding a bicycle, etc.) thereby possibly lacking some common culture elements that may at times turn critical for effective cooperation (e.g. [5, 18]).

V. Conclusion

Social robotics is currently a field of strong interest for at least two reasons: the emerging possibility to have robots helping humans; and the conjecture in evolutionary biology that humans have seen their cognitive capabilities and their unique brain properties develop out of social requirements.

The paper discusses these contexts, shows the continuity through scale changes, namely at collective, nominal and subsystems levels, of cognitive concepts and processes.

On this basis, what has been introduced for individual cognitive agents is mapped onto societies, and in particular individual meditation and thinking become social deliberation and discussing.

Examples with a robot group helping humans in domestic and restaurant applications are also developed and discussed.

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