Human-like Memory Systems for Interactive Robots: Desiderata and Two Case Studies utilizing Grounded Situation Models and Online Social Networking

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Abstract. Although rudimentary memory systems for autonomous agents have existed for quite a while, human-like memory systems which contain extensive episodic, social and affective components, and which can be utilized in order to maintain relationships with humans, have only recently started to appear. Interactive robots are a special case of an autonomous agent, which is physically situated, interacts with humans, and which has sensing and motor abilities. Furthermore, social robots might have regular encounters and interactions with other human or non-human entities, and might maintain relationships with them. In this paper, a set of desiderate for memory systems of companions will be presented, together with case studies of the memory subsystems of two existing robotic systems: first, Ripley the Robot, an interactive manipulator robot arm with vision, dialogue, and a sensorymotor-grounded situation model; and second, Sarah the FaceBot, a social mobile robot with face recognition, dialogue, as well as a social and interaction database which is bi-directionally connected to the FaceBook website. The case studies provide the basis for an interesting discussion involving physical situations, self-models, expectations, and most importantly episodic and social memories, human- or machine- authored, internal or external, private or shared.

1 INTRODUCTION

As autonomous agents mature and their use in the role of artificial companions becomes more widespread, it can be expected that the *importance of human-like memory* systems for such companions will increase. Such artificial companions could be embodied in physical or virtual bodies, and could also be migrating among many different embodiments [1][2]. In order for them to be able to establish and sustain meaningful relationships with humans, fluid and natural communication is one of the prerequisites: and thus *a sharable framework for representing situations and memories as well as communicating about them in natural language* is required. Furthermore, one could even conjecture that a stronger prerequisite might not only include the sharing of the framework for memories, but also of the actual contents. For example, in the FaceBots project [3][4], the central experimental hypothesis is that if a human and a robot have and talk about their *shared episodic memories* (experienced together or communicated), as well as about their *shared friends* and memories with them or about them, then more meaningful and sustainable long-term relationships between human and robot will be created. The more general question thus arises:

Q1: *What features* should a memory system for #artificial# companions have, and *how should it be utilized*, in order to help sustain relationships with humans?

Hard empirical evidence towards answering this two-part question for the case of human-virtual character and human-robot interaction is still at early stages of its development. However, if we temporarily forget about artificial memory systems, and concentrate on work on *human memory*, we enter a subject for which a long history of discussion as well as empirically-supported modelling exists within philosophy [5], as well as the cognitive and the social sciences. In AI, although numerous approaches towards creating memory systems exist, most existing approaches have covered partial aspects only of the numerous intricacies and complexities of human memory. Such approaches ([6-8]), often provide an overtly generalized framework, which however provides adequate specialization for only a small part of the wide range of aspects of human memory. Only recently, have larger-scale attempts towards human-like memory systems started ([9],[10]). Returning back to Q1, and in light of the large corpus of existing work in human memory, one possible answer to the first part of the above question could be:

A1: Let us try to make the *memory systems for artificial companions become human-like too*, so that they can possibly be better "aligned" (i.e. have a shared framework and can be communicated more easily) with those of their human partners.

Thus, the next set of questions follows:

Q2: What are the *main features* of a #human-like# memory system? What are different *ways that they are utilized*, and what might be the *implicit purposes* they might be serving?

In this three-part question we are on much stronger ground as compared to Q1, given the existing history of scholarship. Based on this question, a set of *desiderata* can be formed, towards creating artificial human-like memories, as will be done in the next section. After forming these desiderata, *two specific case studies* of memory systems will be described. First, Ripley: a manipulator arm with vision, language and *situation modelling* abilities. Ripley is equipped with a memory system supporting sensory expectations, and having an episodic memory which includes past states of three models (self, human, environment) and which enables simple mental imagery and awareness of uncertainty. Second, Sarah: a social robot with face recognition, dialogue, as well as a social and interaction database, which is also updated through the *FaceBook website.* Sarah is equipped with an extensive social memory, and a rudimentary on-board episodic memory. However, due to her connection to FaceBook, she effectively has access to a large external memory store, which is human-authored, and shared within a circle of friends. These case studies will be presented, and then discussed in light of the proposed desiderata. Then, we will proceed with a unifying discussion, and finish with a forward-looking conclusion.

2 DESIDERATA FOR HUMAN-LIKE MEMORY SYSTEMS FOR COMPANIONS

In this section, an set of desiderata for human-like memory systems for artificial companions will be proposed[1], which will later provide axis for discussing and comparing different existing attempts. A *concise list* will be first provided, followed by a *short description* of each.

D1) Distinction between Sensory, Short Term, and Long Term
D2) Distinction between Procedural, Semantic & Episodic
D3) Support for awareness of vagueness and uncertainty
D4) Support for mental imagery and perspective flipping
D5) Support for expectation generation and testing
D6) Encoding of physical and mental attributes of self and others
D7) Support for social aspects of memory
D8) Support for affective aspects of memory
D9) Encoding of active and non-active goals
D10) Human-like encoding, retrieval, consolidation & forgetting
D11) Grounding of memory to external reality
D12) Support for explicit as well as implicit memory phenomena
D13) Distillation of episodic to declarative memory
D14) Rich involvement of memory in behaviour and action
D15) Sensory and contextual cueing
D16) Support for interplay of internal with external memory

In more detail, before we utilize the D1-16 in our case studies:

D1) Distinction between Sensory, Short Term, and Long Term

We would like to have at *least three separate levels* of storage – essentially, some implementation inspired by the Atkinson-Shiffrin model [11] and its variants. It is worth noting here that sensory memory is usually *sensory modality-specifi*c, and might take place at *different distances* from the sensor itself in the processing chain, before fusion.

D2) Distinction between Procedural, Semantic & Episodic

Procedural memory accounts for “remembering how”: for example, sensorymotor skills such as picking up a ball. For a robotically embodied companion, this might for example have the form of learnable motor or sensorymotor routines. *Semantic memory* accounts for “remembering that”: for example, that Athens is the capital of modern Greece. Commonsense knowledge databases, such as the knowledge base part of [12], are an example of contents usually held in semantic memory. Also, semantic memory can arise out of observed regularities in events in episodic memory: for example “after the darkness turns to light, the sun will rise” (more on this in D13). *Episodic memory* usually accounts for “remembering something that was experienced”: the sunset yesterday night, my feelings when I first heard this music. Autobiographical memory could be construed as episodic memory augmented with semantic memory content relevant to the self [13]– and plays a central role in numerous philosophical theories regarding personal identity – see for example the memory criterion [14].

D3) Support for awareness of vagueness and uncertainty

A big proportion of beliefs held at any moment, might not be held with absolute certainty - and various *levels of confidence* weightings might be assigned to them. Also, different *granularities of precision* are inherent in different descriptions; a simple spatial example would be: “my cell phone is in the living room” vs. “my cell phone is on the (living room’s) table”. These two reasons, among others, suffice for an illustration of the need for supporting and handling representations of vagueness and uncertainty in memory systems.

D4) Support for mental imagery and perspective flipping

Apart from the arguably pointless and ill-defined mental imagery debate in cognitive science [15], there are various phenomena associated with human memory, such as *viewpoint-taking* [16], that are quite useful to companions too.

D5) Support for expectation generation and testing

Expectations are beliefs about the future, which might or might not be fulfilled, i.e. a form of *prospective* (as contrasted to *retrospective*) memory. Expectations might be derived through predictions on the basis of communicated beliefs or past observations, promise speech acts by other agents etc.

D6) Encoding of physical and mental attributes of self and others

When moving further away from modality-specific sensory memory, usually (a partial exception being [17]) we arrive to some form of a *post-sensory-fusion situation model* (term used in the cognitive science sense of [18]). Within such a model, descriptions of both *passive objects* as well as *agentive entities* exist. The desideratum here is that, within the companion’s memory, the descriptions of agents will not only contain *physical* attributes (i.e. would not deteriorate to a passive object model), but will also contain *mental* attributes, such as estimated beliefs, intentions, and affect of agents. These descriptions could even extend from models of the mental content of agents to models of their cognitive processes[2]. Such models could be created for other agents (through processes associated with having a *theory of mind* in the sense of [20]) or for the self (through metacognitive self-reflective processes).

D7) Support for social aspects of memory

Any companion which represents within its memory not only models of other agents, but also *social relationships* (friendship, acquaintance etc.) among others or among others and the self would qualify for partially achieving this desideratum. Essentially, social memory is an extension of other-models in order to account not only for the transient state and permanent characteristics of other agents, but also for their evolving relations to one another, and to the self.

D8) Support for affective aspects of memory

Emotion and memory are strongly connected [21]. Any memory system in which events would be associated with *affective significance* would qualify for this desideratum, and even more strongly if the associated significance influences in appropriate ways the further processing of these events or their involvement in other cognitive processes.

D9) Encoding of active and non-active goals

Any purposive agent which is involved in planning usually internally represents goals. These goals might often be numerous, and might change status over time: inactive, active, accomplished etc. Goals are also strongly intertwined with attentional effects in memory, resulting in increased availability to certain aspects as compared to others.

D10)Human-like encoding, retrieval, consolidation & forgetting

Human memory comes together with a set of fairly standard processes that operate on its contents; for example forgetting, for which models such as [22] have been proposed.

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[1] This is an initial proposal for desiderata; no claim of completeness is being made. However, we believe it provides a strong foundation.

[2] For example, such models of cognitive processes of other agents could correspond to folk-psychology-inspired models [19], or could start by self-models.

D11) Grounding of memory to external reality

A companion's memory system usually does not (and should not) exist in a void. Its contents should be connected to sensory data, which in turn correlate for example to external physical reality. On the other hand, this connection could also be bi-directional, for example through the creation of sensory expectations (D5). Furthermore, this connection to external reality could be sensor-mediated, or second level, i.e. relying on communicated information from other agents – essentially a form of secondary, indirect grounding.

D12) Support for explicit as well as implicit memory phenomena

Apart from the cases where the act of remembering is comes together with conscious awareness of remembering, there is a large number of other phenomena during which a past experience could result to behavioural modification in the future, without conscious awareness of remembering. These could potentially fall under the category "implicit memory" [23]: for example, various forms of conditioning.

D13) Distillation of episodic to declarative memory

As commented upon in (D1), observed regularities in events stored in episodic memory, such as "after the darkness turns to light, the sun rises" can be turned into semantic knowledge, not tied to a single-shot particular time and place, but having a wider degree of generality. This can for example happen through some form of empirical induction, as the philosophical term would be.

D14) Rich involvement of memory in behaviour and action

Due to the relative simplicity of just creating one more field in a class prototype in an object oriented language, often artificial memory systems are rich in posited representations but quite poor in their utilization towards behavioural modifications or action selection. Memory for example is heavily involved in action selection, as well as inference.

D15) Sensory and contextual cueing

Memory recall is often improved considerably give suitable sensory and contextual cues. Thus, the desideratum here would be to have context-sensitive memory systems for companions, which increase availability of certain items depending on context, and which can furthermore exhibit priming on the basis of suitable sensory cues.

D16) Support for interplay of internal with external memory

Extending upon (D15), one can observe various forms of coupling between, on the one hand, internal representations of memory and processes of remembering, and the natural as well as social environment, on the other. The external part does not merely augment the internal, but in Clark's words [24] external media are "best seen as alien but complementary to the brain's style of storage and computation".

3 RIPLEY THE ROBOT

Ripley [25][26] is a manipulator robot arm equipped with vision and natural language dialogue, and situated in an environment consisting of a table on which objects are placed, and where a human can sit by (figure 1). Ripley's purpose is to act as a conversational helping hand robotic assistant. The software architecture of the robot is based on the Grounded Situation Model (GSM) proposal, and consists of a number of modules intercommunicating with each other through a custom inter-process communication system.

At the center of the GSM architecture, there exists a *standardized representational hierarchy* for modelling situations, together with a *set of standard processes* towards: updating the representations given incoming sensory or linguistic data, gradually reducing certainty in case of sensory inaccessibility, etc. Through the GSM, i.e. these representations and processes, not only object permanence is achieved, but also the situation-model-mediated bidirectional connection between language and the senses: sensory data can map to verbal descriptions, and verbal descriptions can create *sensory expectations* – that can be fulfilled or not fulfilled depending on future incoming sensory data..

Ripley's *dialogue system*, which is single-initiative (human), is able to service three major kinds of speech acts: *Request_For_Information(SA1),Request_For_MotorAction(SA2) and Inform (SA3:* "there is a small object at the right")

A typical dialogue follows for illustration (for more extensive examples, look at [26] as well as the online videos [27]):

(Human places a green ball within the robot's field of view)

H1: Ripley, what size is the red one?

R1: No such object exists

H2: Ripley, where is the green one?

R2: At the left

H3: Ripley, look at the right!

(Robot moves, and now object is not visible, so slowly the positional certainty decreases through a diffusion process)

H4: Ripley, where is the green one?

R4: Most probably at the left

H5: Ripley, there is a blue object at the top

(Sensory expectation created; the robot can speak about the object, and resolve references to it, and awaits for sensory verification when the top area of the table becomes visible)

H6: How big is the blue one?

R6: I have no idea

H7: What color are the objects?

R7: One is red, and the other is blue

(Human places a small blue object at the top)

H8: Ripley, look at the blue object!

(Ripley moves and looks at the top area of the table, where he expects to see the blue object. The expectation is fulfilled, as there was a successful match between sensory expectation and sensory input. Thus, the instantiated token for the blue object is updates through the incoming sensory information)

H9: How big is the blue one?

R9: Small

H10: Hand me the green one

(Ripley moves to the left area of the table, where the most probable position for the green object is, grips the object, hands it towards the direction where the human face was last seen)

H11: Where was the blue one when your head started moving?

R11: Most probably at the top

Figure 1. Ripley the Robot, Human Partner, table and objects

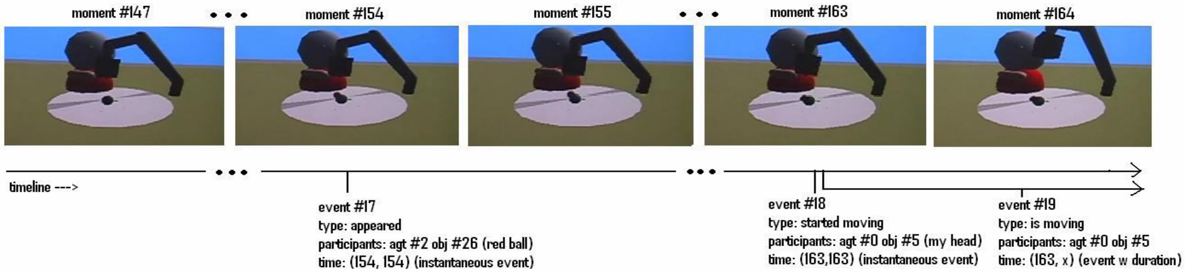

Figure 2. Moments and Events with times, types and participants: the episodic memory of Ripley the Robot

There are a number of points worth making, following this dialogue fragment example: First, notice the mix of all *three kinds of speech acts* mentioned above; H1 is an example of SA1, H10 of SA2, and H5 of SA3. Also, notice H11: an example of a Request_For_Info referring to the past; in which *two kinds of referring expressions* (RE) need to be resolved: Referring to objects (RTO): “the blue one” or Referring to events (RTE): “when your head started moving”. Furthermore, an RTO might either be adjectival / attributive (“the small object at the left”) or using personalpronoun-noun body part names (“your head”). Also, notice the fact that *uncertainty* needs to be taken into account in order to achieve such dialogic capabilities; for at least two kinds of reasons: *Non-continuous availability of sensory data* (when the robot looks away from a region), and *Lack of specificity in verbal descriptions* (“there is an object at the left” gives neither exact position nor size or color).

The required dialogic capabilities, necessitate:

1) Representing properties in a way that supports *sensory* input/expectation as well as *verbal* input/output, with flexible/learnable mappings between words and numerical values, and handling *uncertainty*,
2) Using Situation Models containing models for *objects*, as well as for the *robot* (the “self/me” for example in order to resolve “your head” RTOs), and the *human* (“you” - for example in order to know where to give an object when asked “hand me the...”)
3) Representing *current, past, or imagined* (verbally-instantiated: “there is a ...”) situations

Ripley’s GSM implementation is able to accomplish the above in the following manner (for details, see [25][26]):

1) Four *parallel representations* are used for each property, i.e. single-valued discrete, multi-valued discrete, single-valued continuous, and multi-valued continuous, in order to interface both with words (discrete categories) as well as with the senses (continuous measurements), and in order to handle uncertainty.
2) A representational hierarchy with the “situation” (moment) type at the top level is used. A situation is composed of a description of agents and agent relations (passive objects seen as potentially agentive), and each agent description is broken to a physical description, and a description of postulated mental content, etc.
3) Each current moment (situation) is stored, and the memories of all time instants of the past are also indexed through eight types of *detected primary events*, thus creating Ripley’s episodic memory[3] (figure 2).

Each event consists of a frame with four fields:

UniqueID: #
Type: {create, destroy, appear(get in view), disappear(out of view), start_move, stop_move, start_touch, stop_touch}
Participants: (agt#, obj#), (agt#, obj#)
Time: (start, end)

If we consider both the contents of the current situation with the previous moments as well as events, we get the complete representational contents of Ripley’s GSM. Finally, it is worth noting that there is support for empirical learning of the grounded models of the meaning of adjectives and action / event verbs in Ripley’s architecture, through trainable classifiers [26].

4 SARAH THE FACEBOT

Sarah (figure 3) is a social mobile robot (Activmedia Peoplebot), equipped with a software architecture with modules for face recognition, dialogue, navigation, as well as an onboard social and interaction database, and a real-time connection to the FaceBook website. The purpose of Sarah is to create long-term relationships with human friends, through physical meetings, online meetings, or a mixture of both.

Figure 3. Sarah the FaceBot, FaceBook page & Friends graph

The main experimental hypothesis behind the original creation of FaceBots [3] is that if, during daily conversations between the robot and humans, there is reference to shared memories and to shared friends, then more sustainable as well as meaningful long-term relationships will arise. Sarah, apart from using information from the status and minifeeds of her FaceBook friends while speaking with them, also has her own page on FaceBook, containing her friend list, which also has automatically updated status when she is speaking with somebody. Numerous tangential side-gains were achieved by this interesting combination of interactive robots, face recognition and online social networking; for example, novel algorithms for enhancing face recognition in multi-face pictures given social information, as well as for estimating the friendship graph given massive collections of photos can be found in [4]

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[3] For an interesting information-theoretic approach towards sensorimotor-grounded interaction histories, and an actual implementation, the reader is referred to [28]

[29], and the wider issue of possible roles for artificial agents within human social networks is discussed in [30]. Sarah's software architecture is comprised from multiple modules. The main module we are concerned with here is the social db module – where both social as well as interaction information is located. Also, we will focus on the processes connecting it to natural language dialogue as well as to the FaceBook internet link. A typical dialogue follows: (robot-initiative, in contrast to Ripley).

//Greetings / Recognition (the robot roams around, and stops):

R1:Hello! My name is Sarah. Welcome to the interactive robots and media laboratory. Hi! Are you Panos Toulis?

H1:Yes

(Robot FaceBook status chng:"interacting with Panos Toulis")

//Query of overall state:

R2: Hey, Panos Toulis, are you doing well today?

H2: Yes, pretty well

//General news-based discussion:

R2: Let me tell you some interesting news that I've heard. The architect of the world's tallest building, Adrian Smith, has spoken to the BBC about the 828m high Dubai tower. Have you heard about this? (item taken from BBC News)

H2: Yes

R2b: That's great!

//Robot discusses Facebook status of human:

R4: I see you are chasing robots in the desert

//Robot gives minifeed news about a mutual friend

R5: Did you know that our friend Nikolaos Mavridis has posted a new photo on Facebook?

(information acquired from Facebook minifeed)

H5: No

R5b: I am sending you a message about this to check it out

//Robot remembers past encounter with mutual friend

R6: I saw Nikolaos yesterday evening. He was doing well. (information acquired from interaction database)

//Robot gives status news about a mutual friend

H6: Did you know that our friend Chandan is "waiting for Sarah to have that little sweet conversation with me"?

(information acquired through chandan's Facebook status)

R6: Yes, of course.

//Robot connects an online friend with the human

R7: One of our friends, Nikolaos Mavridis, is online – would you like me to send him a message?

H7: Yes ('Nikolaos, Panos says hello" is sent)

//End of interaction

R8: Hey, Panos, it was nice talking to you! See you later!

The dialogues of the robot follow this overall structure, and are carried out either physically or through facebook chat. As can be seen, they are comprised by a number of basic acts:

Greet, Query State, Tell News, Discuss Human Status, Discuss Minifeed info about Mutual Friend, Refer to old meeting with Mutual Friend, Discuss Status of Mutual Friend, Connect online to Friend, Refer to old meeting with Human, Goodbye

Currently, the order of these acts is fixed, while experimentation about randomization, optimal ordering, repetition etc. is taking place. The find_mutual_friends() method which is utilized in a number of the above acts, uses a query to the online social database, which is periodically updated through facebook. The get_status() and minifeed queries currently directly access FaceBook, as does set_status(), while the discuss old meeting acts utilize the onboard interaction database.

The database contains entries for identities, personal information, friendship relations, and interactions, plus a number of other entries under development. *Interactions* deserve a little more attention. They are effectively comprised of three fields:

F1) Participants: Who participated in the interaction

F2) Time Marks: Beginning and end time of interaction

F3) Description: A single cumulative string containing a verbal description which comprises the gist of the interaction, as contributed by the acts comprising it: "I saw Panos yesterday evening. He was doing well. We discussed about Michalis".

Finally, let us look at the FaceBook page structures, which together with the online status of the human and of mutual friends, are also utilized for a number of the acts taking place. There are many different types of posts in a minifeed: photo & video posts, announcements of friendships, comments to other posts, of liking another post etc. User-adjustable privacy settings in FaceBook restrict global access. Furthermore, each page contains photos, often with tagged faces, whose exploitation is discussed in [29]. Videos of Sarah are available at [30].

5 DISCUSSION

Let us now view the two robots in terms of the desiderata Di. Ripley's memory system contains separate working memory and long-term memory stores (D1). The parametrization of its motor routines, which are executed upon requests for action verbs ("pick up", "hand me"), for which we had demonstrated learning by examples, for a rudimentary procedural memory (D2). No semantic store per se exists; and an all-remembering episodic memory indexed by events is available. Furthermore, apart from simple retrieval (D10) mechanisms (fetch the most recent event matching the verbal description), no forgetting or consolidation processes are supported, and affect (D8) is neither represented within nor effects memory and behaviour. The real strengths of Ripley's system though exist, and are two-fold: first, the offered *bi-directional grounding* to the senses (D11) and second, the *rich capabilities of its working memory system* for: generation and verification of sensory expectations (D5), mental imagery and perspective flipping (D4), representation of agentive models of the self and others (D6 - achieved through "embedded situation models" and virtual allo-centric camera based simulation ToM [26]), and handling of uncertainty (D3) due to lack of specificity or decrease of confidence over time.

Sarah's memory system is quite simple regarding its internal episodic component (D2), and only contains minimal affective (D8) capabilities (i.e. remembering answers to the question: "are you doing well today"). However, it achieves two significant novelties: first, it has quite an *advanced social memory* (D7), *holding friendship relations as well as personal information*, and second, and most importantly, has the direct bidirectional connection to FaceBook, which effectively translates to an interesting complementation of the internal interaction and social databases, with external status-reports for friends and others, with a minifeed digest of their own episodic memories as published on FaceBook etc. Thus, Sarah's memories are effectively extended and blended within the partially-observable external (D16) pool of friendship data and episodic minifeeds of FaceBook. Furthermore, they are utilized effectively (D14) in order to create references to shared memories and friends towards creating long-term relationships. Table 1 provides a cross-comparison of the memory systems of the two robots.

	GSM(Ripley)	FaceBot(Sarah)
D1a) Sensory	~ (visual only)	N
D1b) Short Term	Y	N
D1c) Long Term	Y	Y
D2a) Procedural	~ (motor prog)	N
D2b) Semantic	N	N
D2c) Episodic	Y (moments & events)	Y (interaction memory, onboard&externalFbK)
D3) Vagueness/Uncertain	Y (2 types & processes)	N
D4) Mental Imagery	Y (ego/allo-centric vpt)	N
D5) Expectations	Y (sensory, from sens. detach & verb.descript.)	N
D6) Agentive Models	Y (self/other, beliefs etc)	~(via socialDB & Fbk)
D7) Social Memory	N	Y
D8) Affect	N	~ (storing answer of "are you doing well")
D9) Active Goals	N	N
D10) Retr., Forg, Cons.	N (most recent item)	N (most recent item)
D11) Grounding	Y, bi-direction	~(Facedet,SpeechRec, Fbk reports)
D12) Implicit Memory	N	N
D13) Episodic to Declarat.	N	N
D14) Rich involvement of memory in Behavior	QuestionAnswering, present or past	Dialogue fed mainly by on-board or exter. Mem
D15) Sensor & Ctxt Cues	N	~(socialctx-facerec[28])
D16) Interplay w External	N	Y (Fbk)

Table 1. Cross-comparison of the two memory systems

7 CONCLUSION

The central topic of this paper is the important problem of *designing memory systems suitable for artificial companions,* robotic or virtual, which aspire to create meaningful relationships with humans. We started by posing the question, of *what features* should such memory systems have, and how they should be utilized, towards solving our problem. Given the corpus of available knowledge, we moved towards a slightly modified question, focused on replicating selected features of *human memory* towards artificial systems. Then, we proposed a number of *desiderata* that such memory systems should fulfil, selecting from certain features of human memory, while omitting others. These desiderata, apart from serving as goals, provide a framework for analysis and comparison of existing systems.

Two such systems were presented as *case studies*: First, Ripley, a Grounded-Situation-Model equipped manipulator arm. Second, Sarah, a FaceBook-connected mobile social robot with onboard social and interaction memories. The memory systems of these two companions were later *cross-compared* on the basis of the proposed desiderata, and their strong points as well as shortcomings were discussed. Among the *strong points* of Ripley's memory was bidirectional grounding, agentive models, and uncertainty handling. Sarah on the other hand, was equipped with a social memory as well as what effectively accounts for a partially private and partially public extended memory, which was collaboratively being created through direct experience or potentially multi-hop verbal reports. Of course, not all of the proposed desiderata were fulfilled by the discussed systems.

Thus, numerous *interesting next steps* lie ahead: cross-comparing more existing systems given the desiderata, which could further be refined; creating new memory systems with greater coverage of the required goals; and quite importantly, empirically testing their real effectiveness towards our main goal of meaningful relationships with artificial companions. And as artificial companions are continuously maturing and unleashing new possibilities, our worthy goal is getting constantly closer.

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