

Agent Interaction with Human Systems in Complex Environments: Requirements for Automating the Function of CapCom in Apollo 17

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Abstract

A human-centered approach to computer systems design involves reframing analysis in terms of people interacting with each other, not only human-machine interaction. The primary concern is not how people can interact with computers, but how shall we design computers to help people work together? An analysis of astronaut interactions with CapCom on Earth during one traverse of Apollo 17 shows what kind of information was conveyed and what might be automated today. A variety of agent and robotic technologies are proposed that deal with recurrent problems in communication and coordination during the analyzed traverse.

Data and Analysis Summary

During the 75 hours on the Moon, the Apollo 17 crew conducted three EVAs totaling 22 hours on the lunar surface. These EVAs included lunar rover traverses totaling 36 km, collection of lunar samples at 22 locations in the Taurus-Littrow Valley, deployment or performance of 10 science experiments, and examination and photography of the lunar surface. (Jones, 1999)

The present analysis is motivated by a problem and an opportunity. The problem is that the accomplishments of the Apollo 17 crew during their three days on the moon could not be sustained for weeks at a time, let alone months on Mars. The pace was too fast; the amount of work and difficulties in navigating and using tools too strenuous. Furthermore, the assistance provided by CapCom that made the work efficient at all will be unavailable from Earth during Mars surface operations due to the 10-40 minute roundtrip time delay.

The opportunity arises from the observation that CapCom provided many services that could be easily automated:

146:30:19 Cernan: Say, Bob, where can I get a new set of bags?

146:30:23 Parker: Okay, you want new bags...They'll be under Jack's seat.

Automating the CapCom role would not only make a Mars mission possible, but also make the work less burdensome

than it was on the moon, because many of the verbal interactions with the crew would be replaced by telemetry.

Furthermore, CapCom provides a model of a disembodied agent (not a robot), whose coordination role is distinctly different from the surface crew. *He does not work on the same tasks; he does not carry out any physical work.* Past research emphasis on computers as *robots* has almost totally missed the opportunity to develop *software agents* (Jennings et al., 1998; Alonso, 2002) for assisting in surface exploration. Analysis shows that an agent need not be a collaborator, but an assistant—a remote agent—that logs, tracks, advises, and monitors the work. Obviously, the functions of a physical robot and software agents could be combined. But first we need to understand what services people provide when playing this assistant role from a distance.

To reveal the function of CapCom, I categorized and analyzed examples from Apollo 17 of the interaction between the surface EVA crew (Schmitt and Cernan) and CapCom on Earth (Bob Parker). This analysis is based on three segments of the second EVA during Apollo 17, termed “Orange Soil,” “Traverse to Station 5,” and “Geology Station 5 at Camelot Crater” in the Apollo Lunar Surface Journal (ALSJ; Jones, 1999). Mission elapsed time is continuous from 145:23:48 to 146:56:34 (about 1.5 hrs).

Analysis of the transcripts reveals the following broad categories of information flow and work management functions as the EVA crew interacts with CapCom throughout their work:

1. Reading out information (logging):
 - a. sample bag numbers
 - b. photography frame counts
 - c. rover systems indicators
2. Asking where materials (cans, bags) are located
3. Providing descriptions (geological, equipment condition) for the record
4. Suggesting, requesting, or documenting equipment settings and usage (e.g., suit cooling, film magazine change, dusting radiators)

CapCom actively manages the work on the lunar surface:

1. Indicates elapsed time, time remaining at a site, including walkback (turn around) warnings

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2. States revised plans for substituting, skipping, or reprioritizing work
3. Provides navigation advice, including identifying craters the crew is seeing

These interactions occur in ordinary conversations, with many complications involving disruptive, misheard, and mistaken remarks. These interactions and problems are illustrated further after a discussion of broad technological approaches for dealing with the problems.

Proposed Surface EVA Technologies

Analysis of the transcript suggests four technologies for dramatically improving surface exploration efficiency:

Telemetry between rover and mission support, e.g., rover battery temperature, film frame numbers, bag numbers. Many verbal interactions between the crew and CapCom involve reading information that could be automatically provided by telemetry. Bag numbers might be transmitted by a scanning device on the rover or the suit sleeve.

A “remote agent,” resembling Bob, with whom the crew may have a mixed-initiative dialog about their work, while coordinating this work with a remote crew (at the Hab or Libration Point) and with Earth. During Apollo 17, Bob plays a distinct role, not like a third member of the EVA crew, but as a remote advisor for recording information, helping find and use equipment, and especially to prioritize and time activities. Although it may be tempting to refer to Bob as a member of the EVA team, the crew relates to him very differently from the way they interact with each other. In many respects, Bob is more present to each of them individually than they are to each other. That is, they individually coordinate their actions and narrations more closely with Bob than they do with each other.

A **navigation–task display with a map overlaid, indicating the current location, the route so far, and the planned route with stops**. Timings indicate how much time was spent at previous stops, projected stop times (adjusted for current performance and schedule changes), and time remaining. The display indicates the current activity and time allocation, plus the next activity.

Bag holder and logger—the astronauts spend a lot of time holding a bag open while the other shovels in soil or inserts a rock, or simply carrying sample bags:

146:43:02 Schmitt: Yep. Whew. I've got to have Gene with me since (I) can't carry sample bags.

146:43:09 Parker: Roger.

146:43:10 Schmitt: I probably can if I'm careful; but I keep dropping them..

Having a robot assistant would free up the other crew member. The robot could also automatically scan the bag number, so it needn't be read out loud by the astronaut. This is a classic example of how examining work practice reveals needs that “technology push” would not consider. Assisting the crew in routine tasks should be considered

before “autonomous robots” or doing infrequent big jobs, such as unrolling cables.

The most demanding aspects of this proposed system are understanding natural dialogue, especially interleaved conversations —Crew 1 & Crew 2; CapCom & Crew 1; CapCom & Crew 2—and tracking what the crew is doing.

Crew-CapCom Interactions Apollo 17 EVA 2

Excerpts are sequential (mission elapsed time) within each category. Comments in brackets [...] are in the original transcript.

Crew: Logging sample bag numbers

Bag information includes source of sample and description

145:33:49 Cernan: Bag 509 has got the orange material from, oh, about 2 to 3 inches down.

Bob usually responds “Copy that”

145:34:53 Cernan: Bob, the gray material that's adjacent to the red material is in - what would I say - (bag) 510.

145:35:01 Parker: Copy that.

Descriptions may be elaborated for a turn or two and collaborative:

145:35:37 Schmitt: 511 has the gray from the other side of the orange band.

145:35:41 Cernan: And the other side happens to be the crater side.

145:35:46 Schmitt: That's right. North side.

Bob has to be listening for information directed at him

145:46:10 Schmitt: (To Gene) Okay, I got it. (To Houston) Okay, the basalt (from the large boulder) is in bag 512.

Bob confirms that he has heard correctly

145:48:21 Parker: Okay, and, Jack, I copied - aside from three trench samples - I copied one single bag of basalt samples. Is that correct?

145:48:35 Schmitt: That's right. 512.

145:48:36 Parker: Copy that.

146:09:30 Cernan: Bag 43 Yankee.

146:09:33 Parker: Copy; 43 Yankee.

Schmitt has been scooping soil; Cernan tells Bob which bag was used

146:44:56 Cernan: 455 is that bag number, Bob.

146:44:57 Parker: Copy that.

The crew often works together to take and secure a sample, so descriptions may come from either of them. Here Gene describes Jack's sample (465). Bob anticipates the bag number for the rock sample (466). Then Jack changes the topic back to the previous sample (465) to add information.

146:45:37 Schmitt: (Pouring) I think we better leave it at that.

146:45:43 Cernan: Okay, 465. Pick that other one up and I'll bag it real quick.

146:45:45 Parker: Copy that.

146:45:49 Cernan: That's the soil from on top the rock. And we're taking a piece of the rock itself, which looks pretty much like the other one, Bob. It might be a little bit more vesicular.

146:46:00 Parker: Okay, and that'll be in 466, right?

146:46:06 Cernan: You're right again. Here we are and I'll be able to grab it with my hand. If I put this away. (Pause) Okay. (Pause)

146:46:23 Schmitt: Okay, the soil came from a half a meter in from the soil boundary....

Crew: Logging photography frame counts and planning usage

Frame counts are provided for both the commander (CDR) and lunar module pilot (LMP)

145:55:15 Schmitt: And, Bob, LMP is at (frame count) seven-five

Bob requests a frame readout, telling Schmitt to keep using the same magazine. The readout process serves as an opportunity to note the need to change the magazine. If frame logging is automated, an agent would need to take on this function.

146:53:16 Parker: And how about a frame callout before you get back on, guys.

146:53:19 Cernan: Got it.

146:53:23 Schmitt: Yeah, I need some new...(Responding to Bob) Do you want me to get it (a new magazine) here? (Pause)

146:53:33 Cernan: CDR's at fifty.

146:53:34 Parker: Copy that.

146:53:35 Schmitt: A hundred and seventy.

146:53:36 Parker: Copy one seven zero.

146:53:37 Schmitt: LMP's 170.

146:53:41 Parker: And, Jack, it'd be my opinion, since you're just going back over the same path, that you came up this morning, it's probably not necessary.

146:53:49 Schmitt: Okay, I'll use it until it runs out.

146:53:50 Parker: Okay.

146:27:44 Schmitt: Bob, I have 135 frames. I think I can finish the station, don't you?

146:27:51 Parker: Yes, probably. (Long Pause)

Crew: Logging rover systems indicators

145:53:39 Cernan: (The gravimeter reading is) 670, 012, 501; 670, 012, 501.

146:26:58 Schmitt: Okay. Oh, the (SEP) temperature; they'd like to know.

[Jack goes to the SEP receiver behind his seat.]

146:27:06 Schmitt: Temperature is still about 112.

146:27:08 Parker: Copy that.

As Cernan indicates, it is tedious to be the "voice" of the instruments; notice that he is also interpreting the readings

146:27:27 Parker: Okay, and, Gene, if you're not off the Rover, how about the rest of the Rover readouts?

146:27:33 Cernan: Okay, Bob, I'm off, but I'll get them for you. I'm sorry. I look at them, and they all look good to me. And, you know, I keep forgetting to give them to you.

Crew: Asking where materials are located

145:35:28 Cernan: If I can remember where we put it. Bob, where did we put the small can?

145:35:30 Schmitt: It's in bag 7 under my seat.

Notice how Cernan relies on Bob for this information, even though Schmitt showed before that he knows where things are stored

146:30:19 Cernan: Say, Bob, where can I get a new set of bags?

146:30:23 Parker: Okay, you want new bags...They'll be under Jack's seat.

146:30:26 Schmitt: Under my seat, there's some, Geno.

146:30:30 Cernan: Okay. Just loose?

Crew: Providing descriptions (geological & equipment condition) for the record

146:20:40 Schmitt: Bob, the fragment population - we're at 099/2.0 - is still about the one-percent category of...And it's hard to tell, going into the Sun, what kind of blocks you're dealing with. But my guess is - well, more than a guess - (is that) most of them look like they're slightly vesicular. And, in that regard, resemble the gabbros.

146:21:19 Parker: Okay, copy that.

146:31:47 Schmitt: ... Bob, I have the impression that these blocks are buried up here (and) that the mantle does exist, even on Camelot. There are a few blocks that are lying out on the...(It) looks like they're lying more or less on the surface, but you can attribute those to craters that have disrupted the block field.

146:32:24 Parker: Okay; good observation, Jack.

The crew reports condition of equipment

146:41:54 Cernan: You know I've worn the RTV (Room-Temperature Vulcanizing silicon rubber) off that hammer already.

146:41:57 Schmitt: Yeah, I saw that.

146:42:00 Parker: Roger, 17. Copy that.

Crew, Bob: Suggesting, requesting, or documenting equipment settings and usage

145:34:00 Parker: Copy that. (Long Pause) Okay, we're suggesting Intermediate (cooling) for you, Jack.

145:26:04 Parker: And we're going to want the SEP opened and dusted as well here. With the switches turned off.

146:01:15 Schmitt: Hey, Bob, I recommend that, if we ever do this again, let me get off and pick the charge off when we want to deploy it. It really adds to the fatigue of the hands.

146:06:33 Schmitt: Aah. Stand by on pin 3, gang.

146:06:35 Parker: Copying that. Remember to push it all the way back in, Jack, and start from scratch.

146:00:11 Cernan: Hey, Bob, a note on those (battery) radiators: I have been dusting the covers at every stop, whether that's any help or not.

146:00:19 Parker: Okay; we copy that. (Pause)

Bob: Indicates elapsed time, time remaining at a site, including walkback (turn around) warnings

145:36:52 Parker: ...And the one problem at this station, Jack, is not that...

145:37:01 Parker: ...we can decide priorities between this station or any other station. It's the fact that we're running up against the walkback constraints here in just a very few minutes, about two-zero (20) minutes.

145:43:45 Parker: ...And, 17, for your thought...We have to be leaving here... Not "like". We have to be leaving here in fourteen minutes. On the move, because of walkback constraints.

[Jack goes to the Rover. The walkback constraints are based on an assumed walking speed of 2.7 km/hr. Houston thinks they are 4.2 kilometers from the SEP transmitter and 4 kilometers from the LM, so the walkback would take an assumed 88 minutes. The EVA started at 140:35 and, in 14 minutes, they will be 5 hours 22 minutes into it. An 88-minute walk back would get them back to the LM at 6 hours 50 minutes. Although this estimate undoubtedly differs slightly from the calculation being made in Houston, the important point is that Houston has a firm requirement to get them back at a time close to 7 hours into the EVA.]

145:43:55 Parker: And we'd like to get a quick sample of the basalt up there on the rim, and Gene's stereo pan, and then press on. And I emphasize that it's walkback constraint we're up against in 14 minutes. 13 now.

146:01:02 Cernan: ... (Pause) Bob, how long we been out?

146:01:12 Parker: Stand by. 5 (hours) plus 26 (minutes); 5 plus 26.

146:25:46 Cernan: How's our time, Bob?

146:25:48 Parker: Stand by. We're talking about that now. Stand by. You've got 25 minutes at this station, guys.

We've given you somewhat of an extension here. You're using up some of it back at the LM, but we've given you somewhat of an extension. You've got 25 minutes at this station. The primary priority will be subfloor documented samples, and then subfloor rake soil. (Pause) As you can imagine.

146:26:26 Schmitt: Okay.

Bob interrupts a conversation between the crew to remind them of the priorities, probably because of timing and lack of evidence that they are doing these tasks

146:36:05 Parker: Okay, and a reminder, 17...

146:36:07 Schmitt: Gene, if this is what you mean, it's...

146:36:08 Parker: ...you guys, that the primary priority is the blocks and then a rake soil of the white subfloor soil there. And you've only got 15 minutes before we want you driving back to the LM. Over.

146:36:22 Cernan: Okay. We'll get to work. Okay...

Warnings are given at 25, 15, and 10 minutes—again interrupting the crew's conversation; Bob must be able to hear "Yeah" as a response directed at him.

146:39:57 Parker: Okay, guys...

146:39:58 Schmitt: I'll get a...

146:39:59 Parker: ...looks like you'll be going in about 10 minutes.

146:40:00 Schmitt: ...flight line photo. (Responding to Bob) Yeah. (Pause) (To Gene) Why don't you get a flight line...

Bob: States revised plans for substituting, skipping, or reprioritizing work

145:24:47 Parker: Okay, and the number 1 and 2 priorities at this station will be samples from the crater rim and the pan from the crater rim. Over.

145:36:14 Parker: 17, Houston. We'd like to get the double core here instead of the small can. Double core, please, instead of the small can.

145:36:23 Cernan: Okay.

145:36:24 Schmitt: Did you want it in the orange?

145:36:26 Parker: Roger. That affirm. We can put cores in gray soil all the time.

145:44:30 Parker: Why don't you leave the core there Gene, and you can take your stereo pan while Jack's getting that sample. And then you can get together and ram the core home.

Bob confirms tasks the crew mentions to each other

146:15:13 Cernan: We're coming up to 103 at 2.6 now, so we need a sample up here.

146:15:17 Schmitt: Okay.

146:15:18 Cernan: Okay. 103, 2.5. Anywhere.

146:15:22 Parker: Roger. That's affirm.

A task request is not a simple statement, but may involve a sequence of confirmations and elaboration—Bob appears to repeat the request, but notice that the first command he gives Schmitt gives the objective (get the SEP to cool) but not how to do it (turn it off). Because of the apparent ambiguity, it requires FIVE statements (including Cernan's repetition) before Schmitt is satisfied.

146:26:28 Parker: As you get off, we'd also like to open the SEP and again get that to cool.

146:26:36 Schmitt: Okay. You wanted to turn it Off?

146:26:39 Parker: That's affirm...

146:26:40 Cernan: Turn it off.

146:26:41 Parker: ...turn it Off, open, dust...

146:26:42 Schmitt: You want it off?

146:26:43 Parker: ...the same thing we've been doing to it all aft(ernoon)...(correcting himself) all evening.

146:26:48 Schmitt: Well, it's midday here, Bob. (Pause)

Bob replaces one task for another because of time pressure; this requires confirmation

146:46:41 Parker: Roger. And the present time, we drop the rake soil, we'd just like to get the kilogram of soil somewhere between the boulders - (in) as open (a location) as you can.

...

146:47:00 Schmitt: (Responding to Bob) Oh, you want a kilogram?

146:47:02 Parker: Roger.

146:47:03 Schmitt: From between the boulders?

146:47:04 Parker: Roger. That'll replace the rake soil sample we were going to get. And we'd like you moving in 3 minutes.

146:47:12 Cernan: (Joining Jack and responding to Bob) Okay.

Crew, Bob: Provides navigation advice, including identifying craters they are seeing

145:57:05 Cernan: Okay, I'm Min. Man, I'll tell you, that heading is going to put us right...Okay, Bob, give me a...Dang. Wait a minute.

145:57:15 Parker: The heading you should be generally taking...

145:57:17 Schmitt: Where we at?

145:57:18 Parker: ...toward Victory is 090, Gene.

145:57:23 Cernan: Okay, can you give me a bearing and range at Victory?

145:57:27 Parker: Okay. Stand by.

...

145:57:38 Parker: ...105 and 3.1.

90 seconds later Cernan requests the information again

145:59:03 Cernan: Hey, Bob, I forgot your numbers at Victory. How about giving them to me again?

145:59:05 Parker: Okay. 105, 3.1. And it'll be a heading of 090...

145:59:11 Cernan: Okay. Thank you.

145:59:12 Parker: ...that's the general heading in that direction.

145:59:15 Cernan: Okay. 105, 3.1.

Bob is tracking where they are and what they can see

146:00:27 Schmitt: Okay, sports fans. We're still about on the...Well, I think we moved...Yeah, we moved out into the Tortilla Flat area, I guess. (It's) not very flat.

146:00:43 Parker: That's affirmative. (Pause)

146:00:50 Cernan: Those kind (of shallow craters) I can go through...If I can see them coming.

146:00:54 Schmitt: 102, 3.8. And where's Victory?

146:01:01 Parker: Dead ahead.

With appropriate telemetry, the following is unnecessary

146:03:03 Cernan: We're at 103, 3.4.

146:03:06 Parker: Copy that. (Pause)

A smart system could replace reading the checklist; should this be all verbal?

146:10:11 Cernan: (Looking at checklist page...) Okay, and I want to go about (on a heading of) 120.

Here Bob provides advice, Jack asks for clarification; Bob defers to their understanding. If time delay weren't a factor, an agent could be getting information off-line from Earth or a crew at the Libration Point.

146:17:08 Parker: Copy that. And just press on the same heading you've been carrying there, Gene, and that will get you to Camelot.

146:17:17 Cernan: We want the southwestern edge, huh?

146:17:20 Schmitt: Do you want to go where Station 5 is, Bob (that is, to the planned spot on the southwest rim)?

146:17:23 Parker: That's my understanding, Jack. So press on towards there unless I tell you otherwise.

146:17:29 Schmitt: Well, but you were talking about changing Station 5. I think Station 5 is a pretty good spot (as is).

146:17:34 Parker: Roger. And I think that's where we want to go. I'm just trying to verify that. You can go in that direction, though. I'll get with you if it's not.

146:17:42 Schmitt: Okay. (Pause) It's probably the most concentrated boulder field on Camelot.

146:17:48 Parker: Okay. You know where it is, and we think it's about 092 and 1.6.

146:17:56 Cernan: 092 and 1.6. You know this country...

146:18:00 Parker: Roger. But you know where it is, so you'll find it when you get there.

Crew is confused about what they are seeing; Bob interrupts

146:22:37 Cernan: Yeah, because Horatio's got to be on our right. Well, wait a minute, doggone it.

146:22:41 Schmitt: It's not Horatio, is it?

146:22:43 Cernan: Well, we're at 094, 1.7.

146:22:46 Parker: Stand by. (Pause)

[They are approaching the west rim of Camelot.]

146:22:52 Schmitt: No, I think that's Camelot. Horatio didn't...

146:22:53 Cernan: That's too...That's too...

146:22:54 Schmitt: ...have blocks that far up the rim.

146:22:55 Cernan: ...Let me... Yeah, let me look in the bottom. I'll tell you. I remember.

146:22:58 Schmitt: Yeah.

146:23:00 Parker: That kind of sounds like Camelot to us.

Complicating Aspects of Work Interaction

The crew sometimes mishears or does not listen to each other and CapCom, or misunderstands who is speaking to whom

145:28:50 Cernan: Well, I'm going to clean their glasses so they know we're (not crazy)...(To Fendell) Can you wait a minute on that pan you're taking?

[Gene moves the TV so that he can dust it.]

145:28:56 Schmitt: I already took it.

145:28:57 Cernan: No, I mean the television camera. (To Fendell) I'll put you back where I had you.

Lack of immediate response for advice suggests communication breakdown

146:50:03 Cernan: ... When do you want us to leave, Bob? (No answer; pause)

146:50:20 Cernan: Jack, do you read me?

146:50:21 Schmitt: Yeah. (Pause) Hello, Houston.

146:50:24 Parker: Hello, 17. Loud and clear. We'd like you to leave immediately, if not sooner.

Dialog is mixed-initiative with interleaved topics

Here Bob makes a new request, while Cernan and Schmitt respond in turn to two different tasks they are doing

145:54:03 Parker: And what's your frame count, Jack?

145:54:05 Cernan: Charge number 1.

145:54:07 Schmitt: Okay, (SEP) power's On, recorder's On, the temperature is one-twelve (112).

145:54:16 Parker: I copy that.

CapCom loses track of what the crew is doing

145:54:38 Parker: And, Jack, what's your frame count, please?

145:54:42 Schmitt: Wait, Bob, I can give you that on the Rover.

[TV off]

145:54:45 Parker: Okay. I thought you were on there.

CapCom's remarks were sometimes disruptive and unnecessary

145:55:45 Cernan: That's all right. We got a flag on the Rover, and I'm reading 136 on battery number 2.

145:55:54 Parker: Say again on that one, Gene.

[Schmitt - "My first inclination in the MOCR would have been to turn around and say 'Did anybody get that?,' rather than call right up and distract the crew."]

Under time pressure, decisions need to be made about competing goals

145:49:34 Cernan: I got to take a couple of more pictures at that contact slope over there. You can't see it from where you are, Jack, but I guess we got to leave. Otherwise it would be nice to sample that dark stuff up on top.

145:49:45 Parker: We need you guys rolling in 7 minutes.

Mission control made scheduling decisions that were non-optimal based on opportunities visible to the EVA crew

145:56:21 Parker: Roger. You're moving exactly 37 seconds early.

145:56:28 Cernan: Early!? I could have gotten that dark mantle on the other side of that crater. That's all it would have taken me.

CapCom's decisions were based on interactions with other people; these conversations are (apparently) not documented

145:32:21 Schmitt: Hey, you want any of this bagged in the can, Bob? Canned in the bag...or whatever it is?

145:32:30 Parker: Stand by. They're debating that right now.

The crew works independently and must periodically ascertain each other's status and provide advice to each other

146:34:52 Schmitt: (Turning toward the Rover) How you coming, Geno?

146:34:53 Cernan: Oh, I've got new bags. I've got new mags. I've got everything cleaned up and Mark, gravimeter.

146:35:00 Parker: Copy. Mark that.

The crew confuses LM location (checklist) with SEP transmitter (Rover indicator)

146:55:56 Schmitt: It must be pretty close.

146:55:59 Cernan: You bet your life! (Obviously pleased with himself) I'm reading 085/1.4, and that's what my checklist said.

146:56:03 Parker: Roger. (Pause)

[Again, Gene is misreading his checklist.]

Photographs may be deficient; quick feedback would help

145:39:26 Cernan: Take your picture.

[This photo, like the others Jack has taken since finishing his pan, is badly overexposed.]

Discussion

Anyone looking back over the past few decades must be impressed at what we have accomplished in bringing computer systems to real-world, complex environments—even to imagine assisting astronauts on Mars. In large part, our success is enabled by the smaller, cheaper, and more reliable and networked personal computers of today. That we can imagine networking—with components off-the-shelf—a half-dozen or more supercomputer laptops running on robots, vehicles, and backpacks, distributed over many kilometers (Clancey et al., 2003) is truly astounding from the perspective of those who struggled with punch cards and line printers to develop AI programs in the 1970s.

But with this technology bonus, the tables are turned. The burden is no longer to just show that the computer can do something human-like, such as converse in a dialogue or move down a corridor. Today we must confront the reality of the environments in which we seek to do practical work. The question then becomes, *how can computers help people?* This question is inherently empirical, though the answers will be determined by the new technologies themselves, developed in the context of

use, as is generally well known (e.g., see Greenbaum and Kyng, 1991).

This paper was prepared for a symposium, “Human Interaction with Autonomous Systems in Complex Environments.” My chosen title deliberately reverses the ordering: Agent interactions with human systems. The *system* is not a technology, but the whole combination of people, their tools, and the environment. The symposium abstract states:

Autonomy changes the nature of human tasks and can introduce new risks. Mitigating those risks raises issues in autonomous systems research such as: 1) How to accept task inputs from humans; 2) How to adjust the level of autonomy and/or change the distribution of roles and responsibilities between autonomous systems and humans; 3) How to model humans and their tasks and to what level of detail and; 4) How to facilitate human understanding of the goals, tasks and contexts of autonomous systems....

These issues are real enough, but perhaps especially serious if the autonomous system is *given*, as something that must be *mitigated*. The proposed solutions—accepting inputs, adjusting the roles, modeling people, and facilitating understanding—fit the traditional view of design: From idealized functions (i.e., a superhuman teammate) develop technology, adjust the technology to be more usable, and then train people to cope with the resulting difficulties.

A human-centered approach (e.g., see Norman, 1998) starts instead with the people in their work environment. The science of human interaction—as a perceptual-motor, cognitive, and social phenomenon—becomes the foundation of work system design, including organizations, facilities, tools, procedures. This perspective reframes the problem, to paraphrase the original abstract:

Organizations, facilities, tools, and formal procedures change the nature of human activity and can introduce new opportunities for action. Realizing the advantages raises issues in work systems design research such as: 1) How to determine how people will do their work in complex environments that do not yet exist; 2) How people will communicate with and learn from each other; 3) How people will exchange roles and responsibilities with each other over time; 4) How tools can facilitate routine tasks, as well as action in dangerous, unexpected situations; 5) How to model a *work system*, including people, facilities, geography, tools, and procedures and to what level of detail; and 6) How to facilitate human understanding of the operational capabilities and shortcomings of autonomous systems....

The original perspective of the abstract is not wrong, but it is one-sided. It appears to put the burden on fixing the tools or fixing the people, rather than grounding the original objectives in a better understanding of how people work together and how to facilitate their collaboration.

The symposium abstract suggests “substantial challenges in the design of the autonomous systems themselves and in

the representation and use of the cognitive models underpinning human interaction with autonomous systems.” This fits the human-centered approach, except that again it places the scientific emphasis on studying people interacting with tools, rather than people interacting with each other. (Consider trying to help carpenters by only asking, “How do hammers change the nature of carpentry?”) Thus, the models required are not only cognitive, but social and perceptual-motor (Clancey, 2002a).

In Brahm (Clancey et al., 1998), we have worked for a decade to provide such a modeling framework, in which computer systems (whether databases or robots) are described and simulated side-by-side with models of groups of people and their activities, within a modeled geography including buildings, tables, etc. and other tools, such as sample bags. Furthermore, we have shown through a series of models that it is advantageous to model a full day (and indeed a series of days) in order to understand how work actions (down to the task level) are affected by the context of everyday life (e.g., see Acquisti et al., 2002).

Despite my emphasis on empirical studies of people, some degree of a priori, imaginative, top-down brainstorming is valuable. This suggests roles for technology to assist human exploration, such as the following (NeXT, 2002):

1. Robot tracks an EVA crew member while carrying tools and a camera.
2. Robots do site survey and preparation as well as post-EVA documentation.
3. Robots carry tools, which they hand to the EVA crew member. Robots can also collect designated samples.
4. Robots physically interact with humans via high-level voice commands and gestures.
5. Robots that are true teammates with humans, working on same tasks, responding to natural language, gestures and high-level goals and recognizing human intentions.
6. Synergistic relationship between human and machine with direct, physical connections and prostheses, i.e., super humans augmented with machines.

The list is in many ways consistent with the analysis presented in this paper. However, by focusing on robots (the hammers), notice no mention is made of CapCom or how to facilitate crew members’ interaction with each other. This list, titled “surface assistance metrics,” does not attempt to solve known problems, but rather starts with a single, ill-defined technology—the idea of a robot. This lack of grounding is appropriate for brainstorming, but we must be aware such lists will include unrealistic ideals—“Robots are true teammates with humans, working on the same tasks....” A robot teammate would have higher-order consciousness, implying not just a role, but an identity and *complementary personal projects*, just like a human collaborator. For brainstorming this is fine, but it

has nothing to do with what machines will do on Mars in the next twenty years.

To make practical progress, we need to recognize that there is qualitative difference between the first four metrics and the last two. To make progress—to relate agents and robots to human systems in complex environments—a straightforward empirical approach is possible. As illustrated in this paper, we can begin with simple, ready-at-hand phenomena (including analog settings; Clancey, 2001, 2002b) of people interacting with each other. The focus should be on *how to facilitate human-human interaction*, not how to fix human-machine interaction: “Create tools that are designed to make the maximal use of human perception and understanding without projecting human capacities onto the computer” (Winograd & Flores, 1986, p. 137).

For the case of assisting astronauts exploring a planetary surface, we have the good fortune of having fully documented lunar traverses, transcribed with photographs and digitized video. The six Apollo explorations represent a gold mine of data. The present analysis is just a first, rough cut to show what is available and what kinds of discoveries can be made. Using the same format, robot developers could document and analyze people working together in their domain of choice. Tracking conversations has been shown to be a good heuristic for understanding the work people do in a complex environment (Kukla, 1992). One can then find categories of displays and model-based tools that will support the work. Some of these tools will be agent systems, some of these will be combined with sensors, and others (robots) will also include effectors.

When starting with a complex, perhaps dangerous and resource-scarce environment, such as Mars, analog experience, such as lunar traverses, may reveal a variety of easily defined problems that technology can actually help solve. Starting with how the people are interacting with each other can provide startling changes in perspective. If the astronauts on Apollo are rarely working together, does this mean that a robot who is a “true teammate” would be off working alone? Or might the entire practice of surface exploration be changed by adding a third person? This question is more quickly answered by analyzing appropriate groups of three people, than by adding a rudimentary computer system to a group of two people. This argues that requirements analysis should be empirical, grounded first and foremost in the study of human systems. By better understanding how people interact with each other, we will formulate many practical ideas for what computer systems can do and how they should behave.

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