Chapter 6
Conclusion and Future Work

"Simple can be harder than complex: You have to work hard to get your thinking clean to make it simple. But it's worth it in the end because once you get there, you can move mountains"

Steve Jobs

Contents

6.1 Introduction

This chapter concludes this dissertation and provides an outlook of future research.

The thesis of this dissertation is that a cognitively enhanced control framework for wheelchair navigation can improve collaboration between human– machine. The intuition behind this thesis is that a machine to collaborate with a human, need to consider the basic fact that human often act independently to machine and shows satisficing phenomenon. The proposed solution is that the machine needs to be cognitively enhanced.

This dissertation presents an approach aimed at creating a control framework for a machine that can work as a capable member in human-machine interaction. A cognitively enhanced collaborative architecture has been presented. We have proposed a different notion of navigation controller than one that has been addressed in prior works of IW; that of a wheelchair working with a human as teammate to accomplish its basic navigation task. The basic BDI agent has been extended to allow human-agent collaboration. Formal structures of cBDI and Human–cBDI agent collaboration are presented. This dissertation further explores human way-finding behaviour and present results of a linguistic analysis in identifying strategies of human wayfinding. These strategies are incorporated into the strategic planner which together with the cBDI captures the cognitive concepts of collaboration.

Looking back at our starting point, the origin of inquiry remains but the surrounding looks very different. Steve Jobs' quote at the beginning of this chapter captures this sentiment.

The main contribution of this dissertation is discussed in the following section.

6.2 Contributions

The intelligent system described in the introduction of the thesis is inspired from the contribution of the thesis. Main contribution of this thesis is summarized below:

- **Contribution to Collaborative agent for human agent collaboration.** This dissertation began by presentation of extending BDI architecture to facilitate collaboration with human. We presented a generic architecture for a collaborative agent, cBDI, an extension the BDI architecture. We introduced strategic planner to maintain a human-centric strategy. With the strategic planner, cBDI agent is able to construct collaborative plan. Presented the formal structure of cBDI. We also presented formal structure of Human–cBDI agent collaboration. We presented an example wherein a cBDI agent inhabits the Block-world domain and the cBDI architecture is demonstrated to be adequate for collaborative task.

  We have termed cBDI agent as "generic" architecture for collaboration. The collaborative BDI agent that we have presented in this thesis did not answer all the requirements or full them only partly. One example is given, wherein the cBDI agent inhabits the block world domain. Block World is an experimentation benchmark for planning algorithms [231] and realistic situations can be presented as block world problems. Because of this, we have chosen block world domain to validate cBDI agent. An interesting future work will be to further validation of cBDI in more realistic situations. Further validation would certainly need adjustments/ modifications so that the cBDI agent can be integrated seamlessly in human team.

- **Contribution to human wayfinding literature.** This dissertation has explored human wayfinding behavior with the goal of identifying strategies that a human use under transitivity of transformation of views as well as changed complexity of mazes. Wayfinding experimentation in a maze environment is presented. This dissertation presented results of a linguistic analysis in identifying strategies of human wayfinding. Based on experimental results, we have demonstrated the long-established finding that wayfinding performance is influenced by prior exocentric environment information. We have extended this finding and have been able to show that visual overload resulting out of change in viewing angle and orientation of mazes would not distort the exocentric preview of environment information. Apart from this, based on linguistic data analysis, demonstrated that even under transitive transformation of views and spatial lay-out, wayfinder switch between different strategies.

- **Contribution to collaborative navigation**. This dissertation has presented a framework to control a wheelchair in a way the user wants to control. Presented a framework that is based on the extended BDI architecture where the wayfinding strategies learned from empirical investigation were stored as knowledge base. Presented control framework based on requirements for establishment of collaborative navigation. The framework introduce a concept of negotiation. We have also shown that the controller inherit human centric strategies. Finally controller is demonstrated and evaluated through human subject studies.

  The cognitive collaborative control architecture is modeled as Finite State System and implemented using if-else constructs. The number of states, inputs and transitions are constant. The computational complexity can be statically determined.

6.3 Future Research Directions

In the present state of work, the cognitively enhanced control has some limitations. The term "Contribution towards" in the title of this dissertation express this sentiment. We have identified some of the attributes, which we thought to be important from our sketch of cognitively enhanced control presented in this dissertation.

- Mechanisms to predict human partner intent.
  An important future direction is to have a mechanism for prediction of human intent. In this respect, work of [47] can be useful.

- Mechanisms to learning.
  One of the primary criticism of BDI is the lack of an inherent learning and adapting mechanism. An important future direction is to have a mechanism for learning capability to acquire human partner preferences.

- Mechanisms to negotiate with human based on emotional state.
  Knowledge of human partner's emotional state is important. An important

future direction is to have explicit mechanism to establish negotiation with the human partner based on emotional state.

- How state of mind influence wayfinding strategies?
  An important future direction is to have explicit analysis of humans' state of mind influence on wayfinding strategies.

- Validation with real wheelchair.
  Success of cognitively enhanced collaborative control architecture for wheelchair can only be established once it is put to real wheelchair with real users.

This work contributes towards cognitive enhanced control of navigation. There remain many unexplored complex cognitive behaviour. It needs to extend to include complex cognitive behaviour to further concertize our hypothesis on cognitively enhanced control in physical human-machine collaboration. Some key examples of complex cognitive behaviour are:

- It would be interesting to establish joint attention to identify various other factors related to human preferences.

- Another example of complex cognitive behaviour in context of socio-cognitive interaction is proactive behaviour i.e. planning and acting in advance by anticipating the future needs, problems or changes related to human. It demands reasoning about how and where to behave proactively.

- It would be interesting to understand emotional states, and expressions as parameters in human decision and planning.

The three layered robot control architecture presented in this thesis can be enhanced through a multi-agent approach. This could be based on the previous works of Kuo *et al.* [232], Galindo *et al.* [233] and Ross *et al.* [234] where they showed appropriateness of multi-agent based wheelchair application. In this context it would be interesting to address associated challenges of social cognition. It is important that "particular" behaviour of wheelchair in a human centered environment should reflect social norms and human spatial reasoning. This will help to converge towards a "better" socially intelligent wheelchair. Exploring this perspective will be an interesting future work.

As we build system for physical human-machine collaboration, we will certainly uncover novel ways to do things. It is our hope that viewing the world of human-machine collaboration through a cognitively enhanced control lens may someday allow assistive systems to fulfill their idealistic roles. That would be an immensely exciting future work.

Appendix A

This appendix contains the following related to empirical investigation presented in Chapter 4: (1) Documents given to participants of the user study are shown in Section A.1. (2) Sample document used in Linguistic data analysis is shown in Section A.2 (3) Derivation of F-statistics of joint hypothesis testing in Section A.3.

A1

This section contains documents which were given to participants of the user study, namely the questionnaires.

Part1–Before task

- User name:
  Age:
  Gender:

- Computer experience
  How often do you use a computer?
  Daily □ Weekly □ Monthly □ Rarely □ Never□

- What type of user do you consider yourself?
  Novice □ Experienced □ Developer □

- Video game experience How often do you play video games?
  Daily □ Weekly □ Rarely □ Never□

Part2–After task

- Select one of the option that is in your mind for the solution of maze:
  a. I want to go for fast solution □
  b. I will try it with minimal mental effort □
  c. Let me try first □
- On a scale from 1 to 3 (3 being hard): how do you rate the maze in terms of solving difficulties. 1. □ 2.□ 3. □
- What are the tasks you find easy/difficult to perform?
- How you find your way around mazes and what are the factors that you have taken into account when you solve maze?
- How will you instruct someone to solve the maze?

A2

This section contains sample document filled up by a participant.

Part1–Before task

- User name: partcipant 16
  Age:21
  Gender: Male
- Computer experience
  How often do you use a computer?
  Daily ☑ Weekly □ Monthly □ Rarely □ Never□
- What type of user do you consider yourself?

  novice □ experienced ☑ developer □
- Video game experience How often do you play video games?
  Daily □ Weekly □ Rarely ☑ Never□

Part2–After task

- Select one of the option that is in your mind for the solution of maze:
  a. I want to go for fast solution ☑
  b. I will try it with minimal mental effort☐
  c. Let me try first ☐

- On a scale from 1 to 3 (3being hard): how do you rate the maze in terms of solving difficulties.
  1 ☐ 2☑ 3 ☐

- What are the tasks you find easy/difficult to perform?
  When I find a way, I (sometimes) forgot the way-back [at the current branching position]. So I use figure pointing technique to remember the traversed path. I rate it as 2 due to angle change.

- How you find your way around mazes and what are the factors that you have taken into account when you solve maze?
  Quickly observation of maze
  Avoid block path
  Choose path with displacement pointing towards the goal.
  Also consider reverse path having possible possible displacement towards the current position.

- How will you instruct someone to solve the maze?
  Observed the maze.
  Don't try to remember previously solved path (duo to angle change and reverse position).
  Use your finger as guide(at the deciding / branching points).
  Try to move along the way which is at a displacement towards the goal.
  Don't be hurry (at deciding point).

A3

This section contains derivation of F-statistics of joint hypothesis testing.
Null Hypothesis ($\mathsf{H}_{\mathsf{A}}^{0}$): Wayfinding is not influenced by prior exo-centric preview under change in viewing angle and orientation of target.

Alternative Hypothesis (H_A^a): Wayfinding is influenced by prior exo-centric preview under change in viewing angle and orientation of target.

To test the hypothesis H_A^0, we need to test the joint hypothesis.

$$H_A^0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$$

F-test to evaluate hypothesis=

$$H_A^0 : \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_i$$

A=navigation time of egocentric view(maze1+ maze2)
B=response time of egocentric view(maze1+ maze2)
C=navigation time of array rotated exocentric view(maze1+ maze2)
D=navigation time of array rotated egocentric view(maze1+ maze2)

$$F = (SSR_C - SSR_U/r)/(SSR_U/(n-k-1))$$

where,
r is number of restriction impose, here r=4
k is number of parameters, here k=5
n= sample size, here n=95
n-k is number of degree of freedom
SSR_C restricted residual sum of square
SSR_U unrestricted residual sum of square

$F_{calculated}$=30.50. $F_{critical}$=F(r, n-k-1) is 2.47.

Appendix B

This appendix contains the following related to empirical investigation presented in Chapter 5: (1) Documents given to participants of the user study are shown in Section B.1. (1) Question asked to participants of the user study is shown in Section B.2. (2) Sample sample trajectories executed by participants during robot control mode are shown in Section B.3.

B.1. Cognitive Assessment For Evaluation Of Robotic Wheelchair

Test Part 1–Before Task

- Participant Name:
- Date of Test:
- Signature :

Test Part 2–Test-I

Each question should be asked once (1 mark–correct, 0–for incorrect) name and address for subsequent recall. I am going to give you a name and address. After I have said it, I want you to repeat it. Remember this name and address because I am going to ask you to tell it to me again in a few minutes:

Aditya Kashyap, 39, South-Ex, Karnataka

Time orientation

What is the date?

Clock drawing

- Please mark in all the number to indicate the hours of a clock(correct spacing is required)
- Please mark in the hand to show 10 minutes past eleven o'clock (11.10)
- Can you tell me something that happen in the news recently?

Recall

What was the name and the address I ask you to remember:

Aditya Kashyap
39
South Ex
Karnataka

Test Part 2–Test-II

Each question should asked ones (1-mark for correct, 0 for incorrect)

Arrangement

1. banana, sunrise, chair□□□
2. village, kitchen, baby□□□

Attention

Read the list of digit, 1 digit/sec. Subject has to repeat them in forward order

1. 2-1-8-5-4 □□□□□
2. 7-4-2 □□□
3. serial 3 subtraction starting at 97:□

Test Score
Group-A High cognitive score (Score is greater than 12)
Group-B Low cognitive score (Score is between 11 and less than 11)

B.2. Test Part 3–After Task

This section contains the question which was asked to participants of the user study after completion of all robot control round.

- What is your overall reaction to the driving of the wheelchair?–do you feel in control of the wheelchair in both control method?

  Check your option: (Here, Drive1 is your first driving experience of the chair, Drive2 is your second driving experience of the chair)

  - Drive1 was easy. □
  - Drive2 was easy. □
  - Drive1 was simpler than Drive 2□
  - Drive2 was simpler than Drive1□
  - I do not find any difference □

B.3. Sample Trajectory

This section contains sample trajectories executed by participants during robot control mode.

Sample trajectories during no assistance mode

Figure B-1 to figure B-2 are sample trajectories executed by participants during no assistance mode .

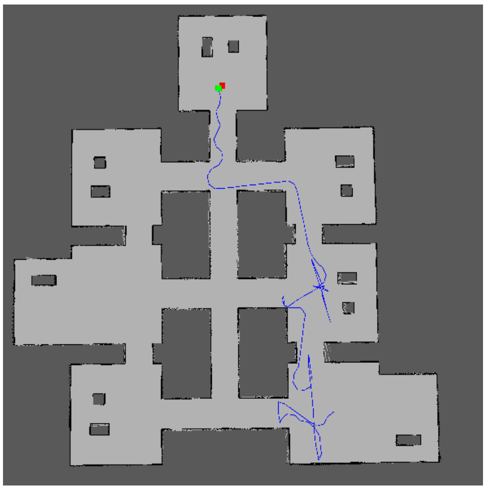

Figure B-1: Figure displays trajectory taken by participant (with low cognitive score) during no assistance mode

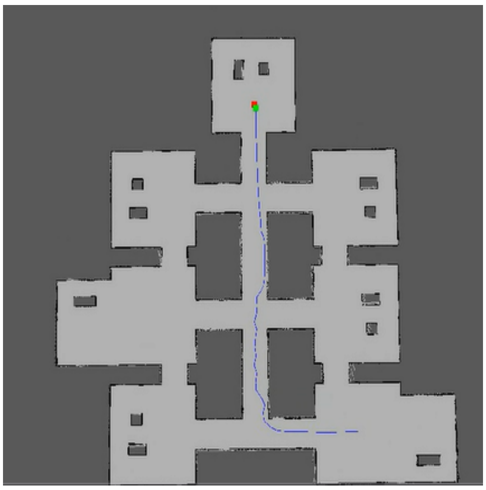

Figure B-2: Figure displays trajectory taken by participant (with high cognitive score) during no assistance mode

Sample trajectories during assistance mode

Figure B-3 to figure B-4 are sample trajectories executed by participants during assistance mode .

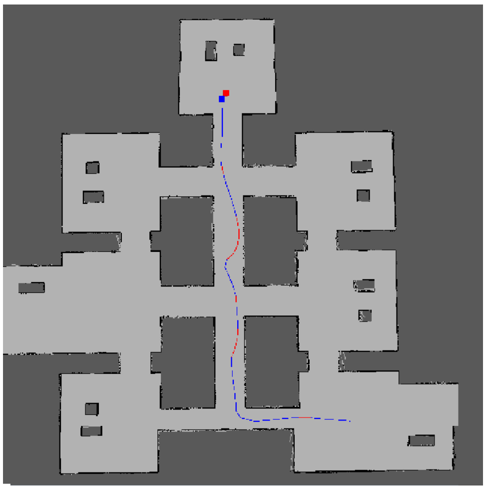

Figure B-3: Figure displays trajectory taken by participant (with low cognitive score) during no assistance mode

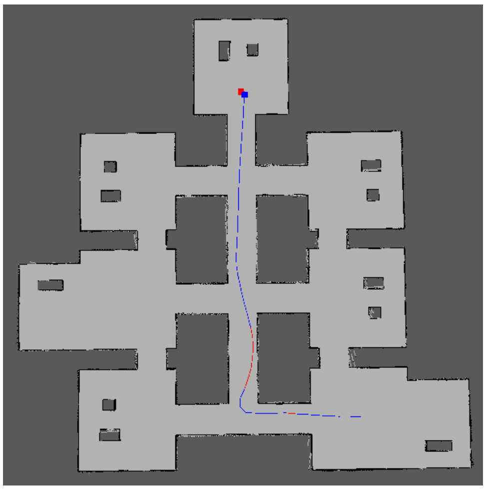

Figure B-4: Figure displays trajectory taken by participant (with high cognitive score) during no assistance mode