

Collaborative Robotic Partner Scheduling

Margaret Pearce, CS 635 Final Project Report

Abstract—Collaborative robots can work safely alongside human workers to complete manufacturing jobs. In this project, optimal task assignments are produced for multiple processes as performed by a single human worker, two human partners, and a human-robot team using the Baxter robot.

I. INTRODUCTION

Collaborative robots are an emerging technology poised to change the way work is done in manufacturing settings. Traditionally, robots perform work that is intentionally isolated from human workers. For safety purposes, robots are placed in a caged in space that is physically separated from humans. Collaborative robots are designed to be safe for humans to be around and work with as a true partner.

The goal of this project is to identify the optimal task breakdown of a process for a human-robot team. Using real-world processes described as a series of tasks, task assignments for a single human worker, a two-person team, and a human-robot team are compared.

II. METHODOLOGY

A. Project Data

The processes represented in this project are based on video data collected from the factory floor of a furniture manufacturing company. Process 1 involves selecting an a top piece and attaching it to a case body. Process 2 has a worker select then attach front pieces to a drawer. Process 3 is an intermediate task that prepares a new case for welding by positioning a metal bar inside of it. Lastly, Process 4 is a kitting station that involves confirming the appropriate parts are selected before placing them securely inside a cardboard box.

After watching the videos, processes were broken down into tasks using Hierarchical Task Analysis. Each video showed multiple iterations of a process, which provided predecessor and timing information. In some cases, predecessors could be logically inferred; for example, a worker cannot screw in a part before the worker has acquired a screwdriver.

It was also evident from the video data that certain tasks needed to be completed by the same worker despite all of the videos showing a single worker per process. A simple example of this scenario is the case where a worker needed to search for a part, select the part, then move the part to a different location in the work cell. The correct part cannot be selected until it has been searched for and located, but in order to partition these tasks

between multiple workers, some degree of knowledge transfer would need to occur. This would introduce complex inefficiencies that are out of the scope of this project, such as adding a secondary “Communicate with predecessor worker” task if and only if a set of related tasks were split between multiple workers and a knowledge transfer needed to occur. To address the issue, data is provided for each task with a predecessor indicating if the same worker needs to complete both tasks.

Start and end times were noted for multiple iterations of each task by watching the videos at a slow rate (x0.25 speed) and marking transitions. The durations for each task were averaged, rounded to the nearest integer, and used as the human task durations.

In the absence of true observed data, the task durations for the Baxter robot leveraged technical specifications from the manufacturer, Rethink Robotics, and estimation techniques. Baxter’s maximum arm speed is 3.3ft/s with no payload (nothing being carried) and 2ft/s with the rated payload (max 5lb) [1]. For tasks that involve Baxter picking up and transporting parts, the speed limit of 2ft/s was used as an estimated speed. Other tasks such as pushing a button or pushing a part down a line used the rate with no payload.

Next, applicable workstations were drawn out roughly to scale in a two-dimensional model. Distances between relevant locations in the workspace were contextualized by comparisons against the human worker (e.g. height, arm length) and objects in the video (e.g. case width and height) to produce consistent estimates of unknown distances. Finally, taking Baxter’s approximate motion plan into consideration, the distance traveled in each task was estimated. Dividing the approximated distances by Baxter’s published arm speeds (based on whether or not the task involved a payload) yielded the robotic time estimates. Tasks involving grasping and gripping were approximated by watching demo videos of Baxter performing pick-and-place tasks using various end effectors. It is worth noting that a robotic worker will not experience fatigue, therefore it is reasonable to assume that Baxter will operate using this maximum arm speed unlike a human worker.

Because the videos show processes assigned to human workers, it is evident that humans are capable of performing all tasks in each process. Robot capabilities were based on technical specifications from the

manufacturer in addition to examining current uses of Baxter in action. For example, one can infer that Baxter is unable to operate a screwdriver because Rethink Robotics does not offer an appropriate end effector capable of holding a screwdriver. Likewise, Baxter does not have sensors sophisticated enough to detect whether the right pressure is being applied or when the screw is level with the surface. Demo and customer videos of Baxter showcase the extent of Baxter’s ability and can verify assumptions on what Baxter is capable of beyond typical “pick and place” work. For example, Baxter can be seen playing Connect Four [2], solving a Rubik’s cube [3], and even brewing coffee [4]. These videos demonstrate that Baxter can maneuver small parts, press buttons, and use basic tools. Nevertheless, if there was uncertainty about whether or not Baxter could perform a task, the default choice was “no” to ensure real-world validity over flexibility.

B. Model

The project consists of three scenarios: a single worker model, a human-human partnership model, and a human-robot partnership model. The single worker model best mimics the video data and establishes a baseline to compare against the two collaborative models. The human-human and human-robot models explore tradeoffs between different types of collaboration. The human-robot model has additional constraints to account for the robot’s limited capabilities and different durations for each task. On the other hand, the human-human model assumes that both workers are capable of performing all tasks at equivalent durations.

Each model was a Mixed Integer Linear Programming problem using linear constraints and objectives with integer (binary) decision variables. All three models use binary decision variables to determine the assignment of tasks between the available workers. Because the single worker model only requires knowing when tasks are completed in relation to one another, a simple ranked model was used. Although this approach was initially attempted for the human-human model, a time-indexed approach was deemed more appropriate. Time indexing simplified rules on predecessors by enabling constraints to say, “If task t1 is a predecessor to task t2, then t1 must be completed in the indexes prior to t2 (regardless of which worker was assigned t1)”.

The models include constraints to enforce predecessor requirements, including “same-worker” restrictions. Practical scheduling constraints are used to ensure workers are only assigned one task at any given time. The models enforce a rule that once a task is started, it must be completed by the same worker without any interruptions before the worker can move on to other tasks. Tasks must be assigned enough time to meet the

expected task duration, which may vary depending on whether a human or robot is assigned to the task. Lastly, Baxter cannot be assigned to any tasks that he is incapable of performing.

III. RESULTS

A. Single Human Model

The results for the single worker model were consistent with the observed video data. The duration of each process was equal to the sum of the average duration of the individual tasks, as expected. Each task was assigned in the order that it is performed in the video.

TABLE I. SINGLE HUMAN WORKER RESULTS

Process	Duration (seconds)
1	75
2	42
3	36
4	53

Fig. 1. Single human worker results

B. Human-human collaboration model

The human-human collaboration model identified which tasks were likely to benefit from a partnership under the best-case circumstances (any worker can complete any task subject to existing constraints). Based on these results, the fourth process is a good candidate for collaboration with a 49.06% duration reduction. The second process is not well suited for collaboration; there are very few opportunities for another worker to provide assistance.

TABLE II. HUMAN-HUMAN COLLABORATION RESULTS

Process	Duration (seconds)	Work Time (seconds)	Idle Time (seconds)	Difference vs. single worker model
1	60	H1: 28 H2: 47	H1: 53.33% H2: 21.67%	20.00%
2	41	H1: 39 H2: 3	H1: 4.88% H2: 92.68%	2.38%
3	30	H1: 10 H2: 10	H1: 66.67% H2: 66.67%	16.67%
4	27	H1: 27 H2: 26	H1: 0.00% H2: 3.70%	49.06%

Fig. 2. Human-human collaboration results

C. Human-robot collaboration model

Result from the human-robot collaboration varied heavily from process to process. The first process shows

an example where Baxter is simply not a good fit. Although the human worker remained busy, the robot was idle for 95.65% of the process duration. Baxter was unable to perform the majority of the tasks due to his 5lb payload limit (pieces lifted in this process are likely more than 5lb) and limited end effector functionality (e.g. Baxter cannot use a screwdriver). However, this process does highlight potential areas of improvement for next generations of collaborative robots.

In the remaining three processes, Baxter matched or improved the process completion time compared to the human-human model. Although process 2 did not demonstrate many opportunities for collaboration to have an impact, Baxter performed just as well as a human partner despite the additional limitations of his capabilities. Processes 3 and 4 showed more opportunities for Baxter to function as an equal partner with the workload more evenly distributed between the workers. Although the idle time is high for process 3, a large amount of time on process as it is designed today involves waiting for the previous station to complete their work and pass a case down the line. The idle time for each worker increased slightly by introducing a robotic partner compared to a human one, but the process was completed in less time overall. Both processes 3 and 4 involve many “pick and place” tasks, highlighting Baxter’s strength in performing this type of work.

TABLE III. HUMAN-ROBOT COLLABORATION RESULTS

Process	Duration (seconds)	Work Time (seconds)	Idle Time (seconds)
1	69	H: 69 R: 3	H: 0.00% R: 95.65%
2	41	H: 49 R: 1	H: 2.44% R: 97.65%
3	29	H: 8 R: 8	H: 72.41% R: 72.41%
4	27	H: 16 R: 15	H: 40.74% R: 44.44%

Fig. 3. Human-robot collaboration results

TABLE IV. HUMAN-ROBOT COLLABORATION RESULTS (CONTINUED)

Process	Difference vs. single worker model	Difference vs. human-human model
1	8.00%	-15.00%
2	2.38%	0.00%
3	19.44%	3.33%
4	49.06%	0.00%

Fig. 4. Human-robot collaboration results (continued)

IV. DISCUSSION

A. Ergonomics

Aside from time performance, there may be other benefits to introducing a robotic worker that are not visible from these results. For example, the human-robot task assignments could be more ergonomically favorable to the human workers. In process 4, Baxter is assigned to tasks that require the most movement around the work cell. Similarly, in process 3 Baxter does all of the reaching and moving of the case from one end of the work cell to the other. One hypothesis could be that Baxter is doing the work that requires the most exertions, therefore minimizing the worker’s risk of injury due to overexertion. A possible extension of this work could attempt to rate each task by its ergonomics and evaluate whether or not the robot improves conditions for the human worker.

B. Limitations

There are several practical limitations to this model. First, the model assumes that a robot will execute a task in the exact same manner as a human worker. In practice, this may not be true. Work cell layouts, tools, and step-by-step task descriptions can be changed to better suit a robotic partner. Second, the model does not account for spatial constraints. Baxter is a compliant robot and is safe for humans to be around, but with a 41” arm length to end-effector plate distance, Baxter can take up a large area of space. It may not be safe to assume that Baxter can work on a process synchronously with a human partner without obstructing the human’s path in some way. Finally, the task duration estimates for Baxter are not precise. Ideally, Baxter would be trained on the line for each task he is capable of doing, then Baxter’s timing could be measured in the same way as human workers. The approach outlined in this paper was the only practical technique within the scope of this project.

C. Challenges

Initially, one goal of this project was to explore the effects of uncertainty on duration time using stochastic programming. As observed in the video data, the time it takes a human worker to complete a given task varies from one iteration to the next. The mean duration was used to make decisions about the best assignments to minimize the overall process duration. However, making decisions based on the mean value is not necessarily the optimal solution. A stochastic programming approach to this problem would use probability distributions of task durations to make assignment decisions, and then the process duration could have been measured based on realizations of multiple scenarios. The implementation proved to be more difficult than anticipated.

ACKNOWLEDGMENT

The author would like to thank Dr. Michael Ferris for his help in completing this project for his class, CS 635 Tools and Environments for Optimization.

APPENDIX A: FILES

The following supplemental files have been included in a .zip file uploaded to the course Dropbox.

File	Description
Project.gms	The project GAMS model
Projectdata.gms	The data file included in project.gms.
Process1 Plan.txt	The task breakdown results of the human-robot partnership for Process 1 (Low Variation Tops)
Process 2 Plan.txt	The task breakdown results of the human-robot partnership for Process 2 (Low Variation Assembly)
Process 3 Plan.txt	The task breakdown results of the human-robot partnership for Process 3 (Case Assembly)
Process 4 Plan.txt	The task breakdown results of the human-robot partnership for Process 4 (Kitting)
Processes – Human Times.xlsx	Observed start and end times for each task in each process from video data as well as average time calculations.
Processes – Robot Times.xlsx	Robot task capabilities, speeds, and time estimates.
Processes – Predecessors.xlsx	Breakdown of the predecessors for each task and whether or not the predecessors need to be completed by the same worker.

REFERENCES

- [1] Rethink Robotics, “Baxter”. Accessed May 2015. http://www.allied-automation.com/wp-content/uploads/2015/02/Baxter_datasheet_5.13.pdf
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- [3] “Baxter Research Robot Solves Rubik’s Cube”. Accessed May 2015. <https://www.youtube.com/watch?v=vF9usYszChU>
- [4] “Baxter Brewing Coffee with Keurig Machine”. Accessed May 2015. <https://www.youtube.com/watch?v=AcxKd-oe-L0>