OPTIMAL MOTION PLANNING OF ROBOTIC SYSTEMS PERFORMING POINT-TO-POINT ELECTRONIC-ASSEMBLY OPERATIONS

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ABSTRACT

This paper reports on the development of a general point-to-point (PTP) motion-planning technique for electronic-assembly systems employing the following multiple coordinated motion devices: an X-Y gantry robot for component pick-and-place operations; a numerically-controlled X-Y table, on which the PCB is located; and, multiple single degree-of-freedom (dof) component-delivery systems. The two primary optimization sub-problems are sequencing of the placement operations and rendezvous planning for the coordinated motion of the robotic devices. This augmented Travelling-Salesperson Problem (TSP+) is solved, via a multi-level approach, using genetic algorithms. As anticipated, the simulation results verify that coordinated robots exhibit superior performance when compared to single-robot systems, providing initial validation of our solution methodology.

KEYWORDS: electronic-component placement, multi-robot systems.

INTRODUCTION

Autonomous robotic systems in industrial environments must be as time efficient as possible. The minimum-time optimization problem is further complicated, however, when two robots are used concurrently in a task-sharing mode. The motion of both robots must then be planned with respect to each other. The specific problem addressed in this paper is the development of a general point-to-point (PTP) motion-planning technique for electronic-assembly systems employing multiple robotic motion devices.

The classical assembly-planning problem has been extensively studied, with numerous attempts at application of research results to robotic-based assembly, [e.g., 1]. A typical sub-problem has been the population of Printed-Circuit Boards (PCBs), [2]. Most proposed solution methods for robotic-assembly-planning problems have their roots in the classical Operation Research (OR) field. Over the past several decades, OR research groups have devised many effective solution approaches to the combinatorial Travelling-Salesperson Problem (TSP), [3]. However in contrast to these single-robot TSPs, where the primary objective is to find the best sequence for N tasks, [4], for multi-robot problems, one must also solve the "rendezvous-point" planning problem. Namely, the latter is an augmented TSP, (TSP+), where the "salesperson" as well as the "cities" have motion capability. In our case, the "salesperson" is the X-Y gantry robot, and the "cities" represent the placement locations on the PCB, or pick locations on the component-delivery systems (CDSs).

Only the literature pertinent to the above TSP+ problem will be reviewed herein. The concentration will be on representative research works in the area of PCB population.

Dubowsky and Blubaugh, [5], present a PTP motion-planning technique for a TSP with only a single robot. They discuss strategies for generating minimum-time motions, rather than minimum distance, for tasks such as electronic-component placement and spot welding. They also briefly address optimal workcell reconfiguration. Ji et al., [6], present a more detailed method for electronic-component placement, also discussing the issues of placement sequencing and optimum bin location. A heuristic method is used to model a standard single-robot electronic-component-placement machine. Leu et al., [7], use genetic algorithms to solve similar electronic-component-placement optimization problems.

Cao et al., [8], address the issue of inspection-task-sequence planning for two coordinated robots. Two SCARA robots are used to investigate the TSP+ problem, where one robot holds the inspection tool and the other holds the part to be inspected. Using a simulated-annealing technique, they were able to plan a PTP inspection route for up to 20 moving points.

In the following sections, we will formalize the robotic TSP+ problem addressed in this paper and present a novel solution methodology.

PROBLEM DEFINITION

In electronic assembly, components must be placed onto the PCB in a time-efficient manner. The first task is the configuration of the board, where component locations are determined subject to objectives and constraints. In this paper, we assume that this task has already been carried out. We also assume that the component-placement machine is picking and placing one component at a time. Although various other placement strategies exist, and are further detailed in the literature, [e.g., 7], our objective is the investigation of the fundamental TSP+ problem.

Figure 1 shows the most generalized physical setup of the placement machine, which we chose to model. The system comprises four main sub-systems: an X-Y gantry robot for component pick-and-place operations; a numerically-controlled X-Y table, on which the PCB is located; and, two identical single-dof multiple-component-delivery systems, with controllable motion in the Y direction. The gantry-robot's workspace includes the workspace of both component-delivery systems and the workspace of the X-Y table. The individual component-delivery devices (bins) are assumed to be attached to each other and move together along the Y axis. Currently, new PCB boards enter and exit the component-placement machine at fixed locations.

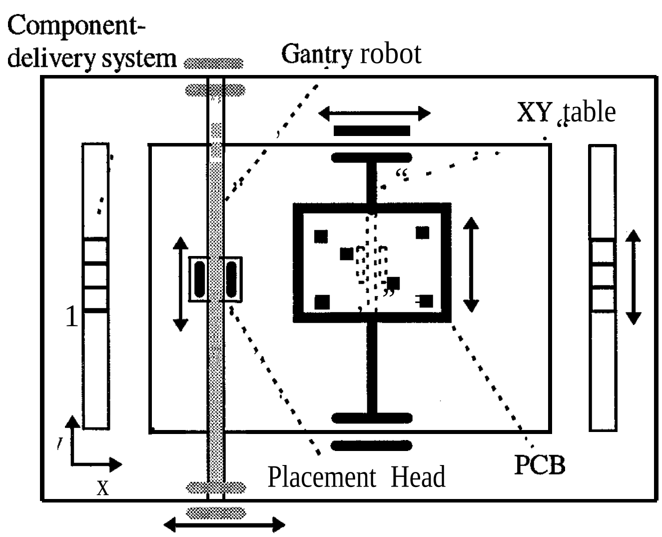


Figure 1: The generalized electronic-component-placement machine configuration.

Four basic system configurations are addressed in this paper: (1) Single-robot TSP, Problem 1, where only the gantry robot moves, and all other sub-systems are fixed at optimal locations; (2) Two-robot TSP+, Problem 2, where both the gantry robot and the component-delivery systems can move, and the X-Y table remains at its optimal location; (3) Two-robot TSP+, Problem 3, where both the gantry robot and the X-Y table can move, and the component-delivery systems (CDSs) remain fixed at their individually-optimized locations; and, (4) Multiple-robot systems TSP+, Problem 4, where all sub-systems can move freely.

Since the components are assumed to be placed sequentially, we identified the placement sequence as a variable common to all the variations of the TSP problem described above. The second task for system configurations (2), (3) and (4) is the solution of the rendezvous-location-planning problem for every pair of interacting robots. For a given sequence, the optimality of a potential set of rendezvous locations can be determined by measuring the overall motion time. To achieve optimal results, individual robot paths between these rendezvous locations must also be optimized. This robot path sub-optimization problem is not addressed in this paper since it has been extensively addressed in other papers, [e.g. 9]. Herein, we simply assume that minimum robot-motion time can be achieved by minimizing the distance travelled by the individual robots.

The first sub-problem is a combinatorial optimization of the component placement sequence, to minimize assembly time. The subsequent rendezvous-planning problem is the process of determining the meeting position of the two robots (the placement robot and the PCB table, or the placement robot and the CDSs). When the combined dof of the two moving sub-systems is above the minimum needed (e.g., 2 dof for planar problems), an infinite number of possible rendezvous-location solutions exist for every potential pick or place exchange between two robots. Therefore, for a given sequence of placements, a corresponding set of optimal rendezvous locations must be determined. For a given PTP (rendezvous) motion, the fastest robot path is normally determined using the robot dynamics.

PROPOSED SOLUTION APPROACH TO TSP+

The most generalized TSP+ optimization problem defined above is solved in this paper using a multi-level approach, where each lower level function provides a value for the parametric set being optimized by the level above it. Component-placement sequencing is the highest level and robot-path planning is the lowest level. To evaluate a given sequence, the sequencing routine calls the rendezvous-location-planning routine, which in turn calls the robot-path-planning routine. The robot-path-planning routine returns an optimized time value used by the rendezvous-location-planning routine to rank the rendezvous locations. The best set of rendezvous locations and the corresponding placement times are returned to the sequencing routine. All other TSP+ sub-problems discussed in Section 2, with one or more of the motion devices fixed in place, can be solved using this approach.

The sequencing sub-problem and rendezvous-location-planning sub-problem are solved herein using a Genetic Algorithm (GA), [10] .This required that the work spaces of the motion devices are discretized in each axis. The rendezvous-location-planning sub-problem must be solved simultaneously for the complete set of placement operations for global optimality. While the GA is well suited to the optimization of discrete problems, the modular approach of our solution method easily allows the rendezvous-point-planning module to be replaced by a continuous-variable optimization method, [e.g., 9].

For the lowest level of optimization, namely the solution of the path planning sub-problem, only kinematic modelling was used. The total assembly time is calculated based on PTP straight-line motion in joint space with maximum available velocity. It is assumed that the robot and the CDS always start at the first pick location. This assumption would normally be true in practice, since the workcell reload time is longer than the time required for the robot and the CDS to move from their last pick-and-place locations to their first rendezvous point.

Figure 2 shows the process of a generic pick-and-place operation. The robot starts at the previous place location, PL_{i-1}, and the CDS starts at the previous pick location, PK_{i-1}. They rendezvous at the current pick location, PK_i. The robot subsequently moves to the rendezvous location with the X-Y table at the current place location, PL_i, and the CDS moves to the next pick location, PK_{i+1}. Note that the X-Y table moves sequentially from previous place location, PL_{i-1}, to the current one, PL_i, while the robot is picking up the component. The paths resulting in the corresponding motion times of the robot, ${}_r t_i$, of the CDS, ${}_d t_i$, and of the X-Y table, ${}_t t_i$, are also shown in Figure 2. Since these motions occur concurrently, the motion with the maximum time dictates the time of the overall single pick-and-place operation, C_i.

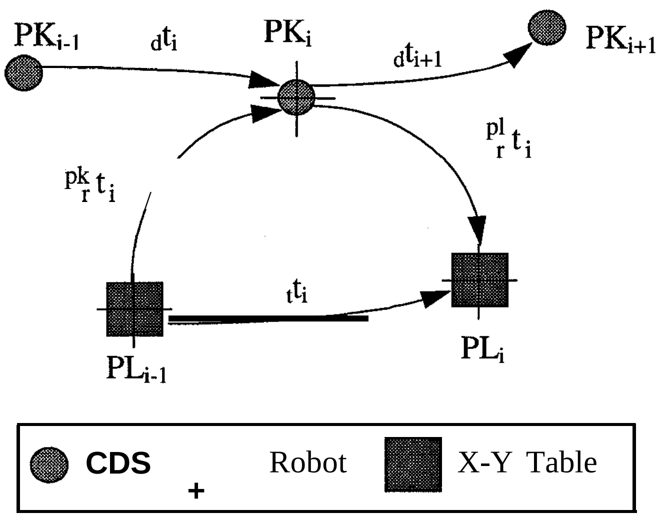


Figure 2: Illustration of cyclic device motion times.

The overall cycle time, t, for the complete population of a PCB, is calculated herein as follows:

$$t = \sum_{i=1}^{N} C_i \tag{1}$$

where:

$$C_i = \max[{}^{pk}_{r}t_i, ({}_{d}t_i - {}^{off}t_i)] + \max[{}^{pl}_{r}t_i, {}_{t}t_i - ({}^{pk}_{r}t_i + {}^{pk}t)] + {}^{pk}c + {}^{pl}c \tag{2}$$

In Equation (2), ‘kc and ${}^{pl}c$ are the constant pick and place times spent by the robot, respectively; and, ${}^{off}t_i$ is the time period that the current CDS has not been involved in a pick operation and has had time to move toward its next pick location. If the i’th component is picked from the same CDS as the (i-1)’th component then;

$${}^{off}t_i = {}^{pl}_{r}t_{i-1} + {}^{pl}c, \tag{3}$$

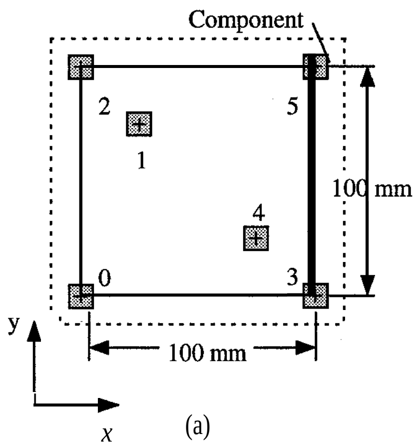
otherwise, it is picked from a different CDS;

$${}^{off}t_i = {}^{pl}_{r}t_{i-1} + {}^{pl}c + \sum_{j=k+1}^{i-1} C_j, \tag{4}$$

where the index k in the summation corresponds to the last component picked from the CDS under consideration.

AN EXAMPLE

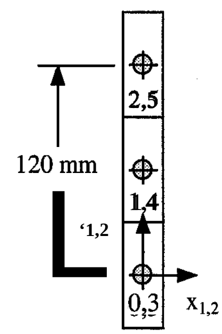
To test our solution method, we chose to optimize a PCB population sequence of six components. The components are placed on a 100mm x 100mm PCB shown in Figure 3(a). Figure 3(b) shows the configuration of the two CDSs. Each CDS consists of a bin with three compartments. The first CDS moves along the line x = -10 and the second CDS moves along the line x = 310. The devices move with the following speeds: 2-dof gantry type pick-and-place robot, 2 m/s (both axes); X-Y table, 0.5 m/s (both axes); and, both CDSs, 1 m/s (Y axis). The workspace of the pick-and-place robot is 300mm x 300mm, the X-Y table is 100mm x 100mm and the CDSs' are 120mm x 20mm. The constant pick and place times are 0.05s and O. 1s, respectively.



(a)

Component Pick and Place
Locations in Device Coordinates

Component Number	Place Position on PCB		Pick Position on CDS	
	x	y	x_1	y
o	0	0	0	0'
1	25	75	0	60
2	0	100	0	120
3	100	0	0	0
4	75	25	0	60
5	100	100	0	120



(b)

Figure 3: (a) The PCB with component positions. (b) One of the two identical CDSs.

The four problem types described in Section 2 were compared with each other and with a non-optimal solution. The latter configuration is identical to that of Problem 1 except that the X-Y table is fixed in the geometric center of the workspace, and the CDSs are fixed in the center of their respective workspaces. Table 1 presents the overall assembly time, and the corresponding optimal component-placement sequence, for each of the problem types. As expected, when more devices are allowed to move (dof increases) the overall assembly time is reduced. Figure 4 shows the resulting placement path of the solution to Problem 4. .

Table 1: Simulation results.

	PCB	Delivery Systems	Optimal Sequence	Total Time (s)	% Improvement w.r.t. the Non-Optimal Setup
Non-Optimal Setup	Fixed (Middle)	Fixed (Middle)	0 2 1 5 4 3	1.621	0.00
Problem 1	Fixed (Optimal)	Fixed (Optimal)	3 5 4 0 1 2	1.582	2.41
Problem 2	Fixed (Optimal)	Moving	5 3 4 0 1 2	1.563	3.59
Problem 3	Moving	Fixed (Optimal)	0 1 2 5 4 3	1.252	22.76
Problem 4	Moving	Moving	5 3 4 0 1 2	1.205	25.66

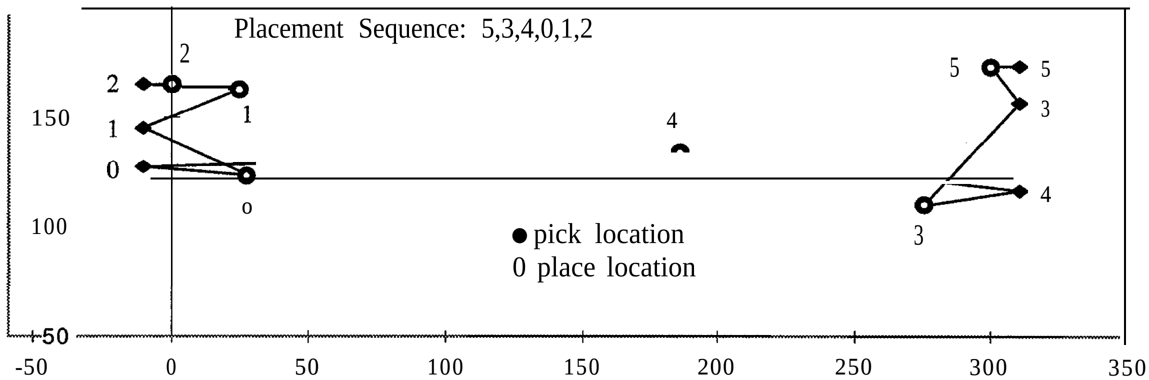


Figure 4: Placement path of Problem 4: Table moving, bins moving.

SUMMARY

Four electronic-assembly configurations were compared in this paper: (1) Single-robot TSP problem, where only the gantry robot moves, and all other sub-systems are fixed at optimal locations; (2) Two-robot TSP+, where both the gantry robot and the component-delivery systems can move, and the X-Y table remains at its optimal location; (3) Two-robot TSP+, where both the gantry robot and the X-Y table can move, and the component-delivery systems (CDSs) remain fixed at their individually-optimized locations; and, (4) Multiple-robot systems TSP+ problem, where all sub-systems can move freely. As expected, our analyses show that, although optimal initial configuration of the assembly machine is a necessity, further improvements in assembly time can be achieved by using multi-robot placement machines.

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