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PRELIMINARY REPORT

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Project Title	Robotic disassembly sequence planning with uncertain interference

Abstract

Remanufacturing is widely considered a part solution to the ever-increasing threat of climate change. With rapid advancement in robotics the potential for autonomous disassembly has been unlocked. To achieve full autonomy, robots must make intelligent and informed decisions. Disassembly sequence planning (DSP) allows robots to visualise assemblies in 3D space and then design optimised disassembly sequences.

This literature review explores the history of DSP methods; the development of a variety of modern optimisation techniques, including a recent study on a novel flatworm algorithm; and the existing attempts to quantify uncertainty through the use of fuzzy data. Research shows that each DSP stage (mode, model, plan) is selected and fine-tuned to achieve a distinct objective; with most of the research prioritising economy and efficiency. Likewise, known uncertainty studies estimate financial viability and not the uncertainty surrounding EoL product condition. Finally, only one paper is found in literature to offer disassembly re-planning – a real-time contingency for when a component removal fails.

Keywords: Remanufacturing, Disassembly Sequence Planning, Optimisation, Uncertainty, Industry 4.0

Literature review

Background

In last 100 years mankind has undergone arguably the most change in human history. In the advent of the industrial era and rapid acceleration in global population, the manufacturing industry has grown and evolved to cater for the masses. Such growth has left the world in imbalance environmentally and economically, and as we enter into these unprecedented times in our worlds history we must adapt to survive.
History itself proves that rapid growth often leads to collapse[1]. Recent estimates indicate that global population will reach 11.2 billion and the climate will warm 3°C-4°C by 2100, resulting in a multitude of challenges this century[2-4]. It is up to us an intelligent species to slow and overcome this impending collapse by implementing advanced technology alongside social and ethical political change.

Remanufacturing is recognised as a key industry in this change. The expanding industry tackles high energy consumption; the over-harvesting of raw materials; and harmful environmental emissions - all with a low cost. Comprehensive research suggests that for core products, input costs can be reduced by as much as 40-60%[5]. Namely, automotive, HDOR equipment, aerospace and even space X are utilising remanufacturing to reduce material and energy costs[6, 7]. Remanufacturing contributes to a circular economy and removes the need for planned obsolescence. With the arrival of Industrie 4.0 and changing public perceptions on climate change the industry has unlimited potential[8, 9].

However, remanufacturing currently contributes a small proportion (1.9%) to the total EU manufacturing industry output (€1.5 trillion in 2015)[6]. This is due to current limitations such as: design for disassembly, collection strategy, purchase intention and government policies etc[10]. Certain studies have also questioned the motives of some remanufacturing companies who prioritise profitability over environmental benefits [11]. Nevertheless, through constant technical development and consideration, the growing industry will soon be a prominent feature of a new, intelligent, industrial era[9].

Disassembly Sequence Planning

Remanufacturing starts with dismantling end-of-life (EoL) products, the condition of which is unknown. Hence, most disassembly processes use human operators for their flexibility. When conducted manually the process is often expensive, labour intensive and cognitively stressful. Robotics can be used to lessen this burden by providing greater productivity and repeatability. Yet, even in highly automated manufacturing scenario, it is still the human operators who are the decision makers and problem solvers who interact with machinery and software when issues arise.

This contrast between 'automated' and 'autonomous' disassembly has encouraged research into disassembly sequence planning (DSP). 'DSP' is a method which allows the robot to design an optimised disassembly sequence and make intelligent decisions on non-deterministic problems. According to Zhou et al. DSP can be split into main three steps: (1) the disassembly mode, (2) building a disassembly model, and (3) applying a selected planning method[12]. Known disassembly modes include: complete, partial, sequential and parallel disassembly which operate as their names suggest. Partial being used to access a particular part, sequential the removal of a component one at a time, and parallel where multiple components can be removed in a single disassembly operation.

In 1984, Bourjault was one of the first the investigate DSP modelling by using man-machine precedence relationships to create an assembly 'tree', or liaison graph[13]. This work was built upon by De Fazio and Whitney in 1987, who applied it to generate assembly sequences by defining connective states with binary variables[14]. Petri net modelling methods started with Bourjault and were later implemented by Kanhera et al. (1993) to generate sequences representing AND/OR graphs[15]. This early theoretical work is compiled in Lambert's 'Disassembly sequencing: A survey' which also includes most DSP methods up to 2003[16]. Since then, these modelling methods have been applied in conjunction with a number of modern sequencing techniques and optimisation algorithms.

In dealing with interlocked structures, Wang, Lan et al. presents a simple and efficient solution by improving upon a space interference matrix which considers remote relations[17, 18]. A recursive strategy is utilised to search for single pair paths, identifying separable pairs if sequential disassembly is not possible. Another method developed by Wang, Lan et al. proposes a 'divide-and-conquer' strategy, which detects subassemblies before disassembly. A hierarchy of sequence plans is created, and thus, interlocking problems are avoided altogether[19]. Both of these methods present valid solutions to interlocked structures, but neither comprise programmed decision making. There is no optimisation of any aspect, other than run time efficiency.

To select an optimum DSP from various feasible alternatives, nature-inspired intelligent algorithms can be employed. Such optimisation algorithms include: Bees, Ant colony, flatworm, genetic algorithms (GA's) etc. Agrawal and Nallamothu et al. present a two-stage software system capable of producing an optimised DSP from a geometric description of an assembly[20]. The program generates space interference matrices in six principle directions from a CAD model, and then utilises GA's to successfully breed a DSP with the objective of minimising the number of re-orientations and tool changes. However, the time for the interference module to complete can be expressed as a quadratic polynomial and consequently a large number of parts, in excess of approx. 100, would see extensive processing times. Not to mention the genetic algorithm cannot be used for online, or real time, decision making because of its complexity.

GA's feature diversity via a probability-based selection strategy, which allows a mixture of optimum solutions to survive each generation. In a recent journal Tseng, Huang et al. adapt conventional GA's by replacing crossover, mutation and replication mechanisms with growth, fracture and regeneration mechanisms; characteristics typical of a flatworm[21]. In this case only a single individual is used to grow the next generations. When compared with traditional GA's and two ant colony algorithms the novel flatworm algorithm is found to solve problems of increasing complexity with superior speed and quality. Notably, the paper utilises the concept of a penalty value matrix to assess the cost of changing direction and tooling. A further question is whether this matrix could be used to model uncertainty?

Previous research has attempted to model uncertainty using fuzzy data sets. Wang and Allada evaluated the 'serviceability' of products with fuzzy neural networks to assess the cost-benefit of remanufacturing earlier in the design process[22]. Similarly, Ying and Mengchu et al. mathematically modelled uncertainty surrounding human factors (skill and salary) and proposed a fuzzy petri-net based method to select an optimum DSP [23]. Firstly, like much of the literature on remanufacturing, these papers focus on economic viability rather than environmental benefit. Secondly, both models do not consider uncertainty surrounding product condition in relation to DSP. Ideally, a live learning-based method would construct DSP's based on the knowledge of past interactions.

Bees algorithm is a well-known heuristic search method which mimics the efficient foraging behaviour of honey bees. A method is developed by Liu, Zhou et al. to minimise robotic cycle time[24]. The paper shows that when compared with GA and particle swarm optimisation both enhanced and improved bees algorithms are far superior in quality, although with slightly longer processing times. However, in current studies, bees can only be used for complete disassembly. Furthermore, the long iterative processing times limit this method to approx. 200 parts.

The Gap

Up to now, the listed literature does not allow for online decision making. From known literature, only Laili, Tao et al. allows for real-time optimisation by considering bees algorithm in combination with the two pointer-method [25]. In this study the algorithm executes either the most difficult or inexpensive task first, depending the distribution of tasks cost and reliability respectively. The two-pointer method can generate hierarchical sequences for both static and dynamic disassembly. If a component were to fail during operation, the strategy ignores previously removed components and reconfigures a new DSP for the remaining assembly. To our knowledge, no prior studies have addressed failure in DSP, and although this method is fantastic at prioritising cost and reliability, it still lacks a learning mechanism. The program cannot predict uncertainties in product condition and cannot learn from past experience. These are two issues I intend to address.

From the literature reviewed there are notable areas for further exploration. Firstly, the few studies researching stochastic objectives are limited to estimating or maximising economic benefit. None address the issue of EoL product condition for disassembly, and the consequent environmental benefits. Secondly, most DSP methods cannot predict uncertainty or adapt to unexpected failure – more research needs to be conducted in this area. Finally, to my knowledge, none of the listed methods can learn from past experience.

By utilising a ranking scheme to assess predicted product condition, similar to methods used in [21], [23] and [26], I intend quantify a live uncertainty interference matrix. Which through Monte-Carlo forward uncertainty propagation and iterative estimation, I will teach the program to make informed real time removal decisions based upon the success of previous actions. If successful, this study will allow for real time uncertainty prediction, re-evaluation and decision making. Future studies could allow for compound learning from product to product, and with the advent of industrie 4.0, robots could communicate through the cloud about EoL product quality and the uncertainty of particular actions[8].

Project Aim & Objectives

Aim

Develop a disassembly sequence planning method for products with uncertain interference conditions

Objectives

1. Study existing literature to investigate the best method of modelling uncertain interference within space interference matrices.
2. Design a disassembly re-planning process to allow for failure.
3. Understand and implement forward uncertainty propagation and iterative estimation methods.

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