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Productivity/energy optimisation of trajectories and coordination for cyclic multi-robot systems

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ABSTRACT

The coordination of cyclic multi-robot systems is a critical issue to avoid collisions but also to obtain the shortest cycle-time. This paper presents a novel methodology for trajectory and coordination optimisation of cyclic multi-robot systems. Both velocity tuning and time delays are used to coordinate the robots that operate in close proximity and avoid collisions. The novel element is the non-linear programming optimisation model that directly co-adjusts the multi-robot coordination during the trajectory optimisation, which allows optimising these as one problem. The methodology is demonstrated for productivity/smoothness optimisation, and for energy efficiency optimisation. An experimental validation is done for a real-world case study that considers the multi-robot material handling system of a multi-stage tandem press line. The results show that the productivity optimisation with the methodology is competitive compared to previous research and that substantial improvements can be achieved, e.g. up to 50% smoother trajectories and 14% reduction in energy consumption for the same productivity. This paper addresses the current lack of systematic methodologies for generating optimal coordinated trajectories for cyclic multi-robot systems to improve the productivity, smoothness, and energy efficiency.

1. Introduction

The multi-robot coordination determines the relative motions of the robots to each other. Its purpose is to avoid any collisions between them but it is furthermore also important to reduce the cycle-time of system. Hence, this is thus a critical aspect in the motion planning of cyclic systems [1], i.e. the operations are repeated in cycles at a constant frequency (for example in high-volume production), where the cycle-time directly determines the productivity. For example, Pellegrinelli et al. [2] investigate this issue for the motion planning of multi-robot spot-welding cells for car-body assembly, and combined with task allocation and cell design. A detailed analysis of different coordination methods is presented by Todt et al. [3], and furthermore Yan et al. [4] discuss different methods for multi-robot coordination of mobile robots.

On the one hand, a distinction is made between *online* and *offline* multi-robot coordination methods [3]. Online methods resolve the multi-robot coordination during the task execution, i.e. while the robots are already moving [5–8], whereas offline methods determine the multi-robot coordination before the task execution [2,9,10]. This paper focuses on an offline multi-robot coordination method.

On the other hand are there two main categories for multi-robot coordination, i.e. *centralised* and *decoupled* [11]. A *centralised approach* plans and coordinates the robot motions directly in the combined configuration-space (C-Space) of all robots. Although effective, this approach is typically rather inefficient due to the high dimensionality of this spatial representation. A *decoupled approach* first plans the motions individually for each robot operation, and uses a coordination method afterwards for the collision avoidance either by using time-delays [10,12,13], velocity tuning [7,14,15] or path modification [9]. The decomposition of the coordination problem makes these decoupled coordination methods more efficient but there is a sacrifice in completeness [11]. A decoupled approach is adopted in this work, and both velocity tuning and time-delays are used together by the coordination method. Furthermore, rather few previous works consider cyclic systems, even though this is often relevant for manufacturing systems.

Velocity tuning (i.e. changing the timing-function) of the trajectories also affects the robots' energy consumption [16]. The energy efficiency of robot systems is becoming more and more important for the manufacturing industry as discussed by Paryanto et al. [17]. Most interestingly for this work, several recent research works specifically focus on non-intrusive methods to improve robots' energy efficiency by modifying the trajectory [16,18–20], and give substantial reductions of the energy consumption. Although some of these energy minimisation methods are applicable for multi-robot systems [16,20], the collision-avoidance is guar-

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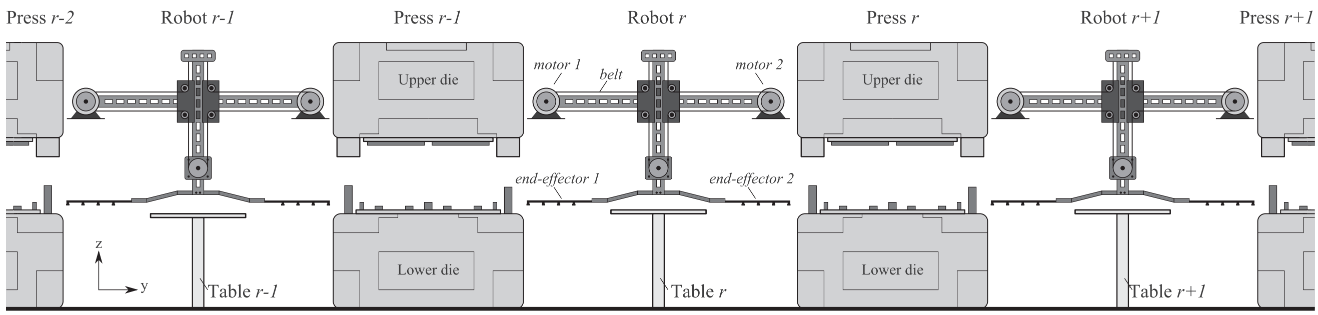

Fig. 1. Multi-stage tandem sheet metal press line of the case study.

anteed by using predefined restricted zones for the robots to avoid that they operate in close proximity. The robots are then forced to wait until their restricted zone is free, which introduces longer time-delays between the operations. There is thus a need for a multi-robot coordination methodology, which operate cyclical and in close proximity, that can generate optimal coordinated trajectories to minimise the cycle-time or the robots' energy consumption.

The contribution of this paper is the proposed methodology that efficiently integrates trajectory optimisation with predefined paths and a decoupled coordination method for cyclic multi-robot systems. A unique element is that both time-delays and velocity tuning are used to avoid collisions between the robots that operate in close proximity. The novelty of the proposed methodology is that the used non-linear programming optimisation model directly co-adjusts the multi-robot coordination and recalculates the resulting cycle-time when the robot trajectories are modified, i.e. when changing the optimisation variables of the trajectories. This methodology generates the coordinated trajectories offline. It is proposed for productivity- or energy-optimisation. It does not require a dynamic model of the robots, which is an advantage since this is often not (directly) available. The collision-avoidance is based directly on the robots' movements relative to each other in order to avoid the corresponding interferences between the geometries of the robots, end-effectors, handled parts, etc. This thus addresses the current lack of systematic methodologies for generating optimal coordinated trajectories for cyclic multi-robot systems.

The evaluation of the proposed methodology is done for a real-world case study that considers the multi-robot material handling system of a multi-stage tandem sheet metal press line. The press line is illustrated in Fig. 1. The material handling in the press line is referred to as *press line tending*, which is described in the next section. This evaluation shows that the optimised trajectories make the robots operate safely in close proximity in order to minimise the cycle-time, while also ensuring smooth motions to avoid excessive wear of the robots. The proposed methodology is furthermore also demonstrated for optimising the coordinated trajectories to reduce the robots' energy consumption while guaranteeing a predefined cycle-time.

2. Press line tending

The material handling in a multi-stage tandem sheet metal press line is considered as a case study in this paper. It is a typical example of a multi-robot system where the coordination is critical for the productivity. As shown in Fig. 1, a *tandem press line* is a line of individual presses with in between material handling devices (i.e. robots) to transport the sheet metal plates from press to press. These press lines typically include 4 to 6 presses.

During the stamping operation, the upper die of the press moves downwards and forms the plate by pressing it onto the lower die, and then afterwards the upper die moves upwards again. The stamped plates are first unloaded onto an intermediate table/fixture, before being loaded in the next press. This allows the table/fixture to reorient and/or reposition the plate, if necessary. The material handling robots in the considered press line are *2D-belt robots* [21] or also called *H-bots* [22]. It has 2 joint motors that drive a timing belt so that it has 2 degrees-of-freedom. Hence, in Fig. 1, the robots perform translations in the *yz*-plane to transfer the sheet metal plates.

Two end-effectors, which grip the sheet metal plates using vacuum-cups, are mounted on each 2D-belt robot in the considered press line. These are indicated as end-effector *1* and *2* on Robot *r* in Fig. 1. The robots can thereby pick up two plates simultaneously. For example in Fig. 1, Robot *r* simultaneously picks up the stamped plate from Press *r-1* with end-effector *1* and the plate from Table *r* with end-effector *2*. Next, the plate in end-effector *1* is then placed on Table *r*, while at the same time the plate in end-effector *2* is loaded into Press *r*. The advantage of this is that Robot *r* unloads Press *r-1* and loads Press *r* in a single motion. More specifically, the operation sequence for a cycle of Press *r* in Fig. 1 is as follows:

1. Robot *r* loads Press *r* (after unloading Press *r-1*),
2. Press *r* performs the stamping operation,
3. Robot *r + 1* unloads Press *r* (and loads Press *r + 1*),

and this is repeated in the next cycle, for the next plate. It is important to note that an operation can only be started after the robot or press has completed its previous operation(s). This can result in additional time-delays between operations and cycles.

To obtain the shortest cycle-time for the press line, the time-delays between the operations and cycles must be kept minimal by executing the operations (nearly) simultaneously, as much as possible, without colliding with each other. For the press line, this means that:

1. Stamping starts during loading (see Fig. 2a),
2. Unloading starts during stamping (see Fig. 2b),
3. Loading starts during unloading (see Fig. 2c),

and also that the robots and presses operate in close proximity. The *multi-robot coordination* for this system refers to planning optimal trajectories and determining minimal time-delays between the operations and cycles to avoid collisions, but also obtain a minimal cycle-time. The trajectories and multi-robot coordination obviously affect each other directly, and these need thus to be considered together as one problem. Furthermore, due to the specific cyclic operation sequence, it becomes necessary to consider all presses and robots in the line simultaneously, which makes it a challenging optimisation problem.

The current industrial practice is that the line-operators manually tune the trajectories and multi-robot coordination online, by trial-and-error, during production [23]. The available tuning parameters are the robots' velocities and time-delays. This practice is not very reliable because it highly depends on the operator's expertise and experience. It is also a time-consuming cumbersome task that is not without risk of damaging the equipment. A press die is typically one-of-a-kind and is very time-consuming to manufacture. Consequently, damaging a press die would delay in production, which is usually unacceptable for the industry. The operators are thus always extremely cautious during the