Optimization of the Reconfiguration Planning of Handling Systems based on Parallel Manipulators with Delta-Like Architecture

Jan Brinker[1], Marco Lübbecke[2], Yukio Takeda[3], Burkhard Corves[1]

***Abstract*—Future production systems must meet the continual demands for improved productivity and energy efficiency. Being flexible and adaptable, reconfigurable systems offer great opportunities to face these challenges. Against this background, this study is concerned with the reconfiguration planning of Delta-like parallel robots. Following the trend of equipping the original Delta robot with additional rotational dof, a potential analysis reveals a great variety of dimensional and functional reconfiguration possibilities. Based on this, the reconfiguration planning is optimized applying operations research techniques. In this approach, a fixed number of configurations is optimally selected from the entire configuration space and simultaneously allocated to a set of handling tasks in a most energy efficient way. Each allocation's energy consumption is efficiently computed using Kane's inverse dynamics formulation. The outcome of a case study demonstrates the general applicability and energy-saving potential of the proposed method.**

***Index Terms*—Delta Robots, Industrial Robots, Inverse Dynamics Formulation, Parallel Robots, Reconfiguration Planning**

I. INTRODUCTION

THE fourth industrial revolution continues to drive the digitalization of production and cooperative networks of employees and machines. Future production systems will be characterized by intelligent acquisition of information and targeted use of smart data (e.g., process monitoring by machine-integrated sensors, online process simulation, or multiphysics modeling). In this context, highly efficient and flexible systems evolve to establish sustainable automation concepts and finally allow for fast adaptation to changing market needs. Even though robotics technology has led to a high level of automation in large-scale manufacturing industries, key aspects of future strategies still focus on increased flexibility and agility in order to serve a broader range of manufacturing technologies and products. Key technology targets for future production systems are, among others, efficient (re-)configurability, adaptability, and energy efficiency [1]. Essential success factors of all three targets are tools to (automatically) identify suitable (re-)configuration patterns of the mechanical system in order to fulfill functional requirements determined by current process specifications. Thus, the configuration of a system can be optimized in accordance with process or task specific requirements from a technological and economic viewpoint.

Systems for highly dynamic handling tasks require a high payload-to-weight ratio, a high positioning accuracy as well as excellent stiffness characteristics. Parallel manipulators meet these requirements by their architecture with frame-based actuation and thus low moving masses. The most widely spread manipulators within the niche market of parallel robotics are the 6-dof Gough/Stewart platform [2], [3] and the 4-dof Delta robot [4] as commonly used for highly dynamic flight or driving simulation and high-speed pick-and-place applications with light-weight objects, respectively. In recent years, the design of the latter has been modified significantly extending its field of application to handling tasks with up to six dof (e.g., assorting, tooling, or measuring tasks) and/or with heavy-weight objects (e.g., stacking or packing tasks). As already noted by the inventor Clavel [5], the Delta robot is distinguished by its modularity and the fact that some components are found in several identical copies in one robot. Thus, to generate a range of robot configurations, it is possible to allow several dimensional groups for select components of the robot. Against this background, the Delta robot is well-suited for the following investigations in the field of reconfiguration planning.

First, we briefly introduce general reconfigurable systems and reconfigurable Delta-like robots focusing on dimensional and functional reconfiguration possibilities. A novel approach is presented applying techniques of operations research to the optimization of the reconfiguration planning of robotic systems. Finally, a case study demonstrates the energy-saving potential for industrial applications.

Manuscript received February 15, 2017; accepted May 5, 2017.

This paper was recommended for publication by Editor upon evaluation of the Associate Editor and Reviewers' comments. This work is supported by the German Academic Exchange Service (DAAD) with funds from the Federal Foreign Office (FFO).

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Digital Object Identifier (DOI): see top of this page.

II. TYPES OF RECONFIGURATION

The term reconfiguration includes a range of definitions. Accordingly, a reconfigurable system "can reversibly achieve distinct configurations (or states), through alteration of system form or function, in order to achieve a desired outcome within acceptable reconfiguration time and cost" [6]. It is thus "designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components" [7]. A generally recognized definition is that "reconfigurability is the ability to repeatedly change and rearrange the components of a system in a cost-effective way" [8].

In respect of parallel robots, different mutually influential types of reconfiguration can be identified. Examples refer to:

a) modularity: Robot components, also called building blocks, are classified into fixed-dimension modules (e.g., actuators, passive joints, and tools) and variable-dimension modules (e.g., rigid links, the fixed platform, and the mobile platform). Different configurations can then be achieved by changing the number, types, and arrangement of modules [9].

b) state: It is distinguished between two states: static and dynamic reconfiguration. Whereas in static reconfiguration components are changed or rearranged while the robot is switched off, dynamic reconfiguration includes online adaption of link dimensions and/or locking of joints as well as switching of operation modes [10]. Dynamic reconfiguration may also be defined by variable grasping points and integrating or removing kinematic chains of a handling system during manipulation [11].

c) morphing: Three types of morphing can be identified: geometry morphing (variation of link dimensions and/or arrangement of kinematic chains without changing the kinematic architecture), topology morphing (variation of links as well as type and sequence of joints in order to obtain different dof), and group morphing (several modular robots are grouped and/or separated to perform a joint task) [12], [13].

According to a recent classification in [14], reconfiguration is mainly characterized by changing modules within the varied architectures, switching operation modes (i.e., changing the mobility) by passing through singular configurations, changing the geometric relations of joints and links, and locking joints. Also, it is worth noting that current research in the community of parallel robotics strongly focusses on reconfigurable parallel robots with multiple operation modes, which are also known as robots changing the group of motion, robots with bifurcation of motion, or disassembly-free reconfigurable robots [15]. Moreover, extensive overviews on reconfigurable parallel manipulators can be found in [8], [14], [16], [17], [18], [19], [20]. Apart from that, a survey and historical review on general reconfigurable systems can be found in [6] and [7], respectively.

III. RECONFIGURABLE DELTA-LIKE ROBOTS

The basic architecture of the Delta robot comprises three kinematic chains of the type $\underline{R}(SS)_2$ (where R stands for a revolute joint and S for a spherical joint). In each kinematic chain, frame-based rotary actuation is used to drive the proximal link which in turn is connected to the moving platform by a spatial parallelogram (in which the two parallel connecting rods are denoted as distal link in the following). With this design, the platform is restricted to three translational dof. Fig. 1 depicts the geometric relations and notations of the classical 3-dof Delta variant. Accordingly, several identical modules can be identified allowing for reconfiguration by varying their dimensions.

After the expiration of the original Delta patents in 2007, modified Delta variants entered the market. New variants particularly involve designs that enable additional rotational dof. For example, 4-dof fully-parallel versions comprise an additional kinematic chain which, regarding reconfiguration possibilities, either require a complex architecture due to the so-called articulated moving platform (e.g., Adept Quattro) or careful arrangement of the four kinematic chains amongst each other using a rigid moving platform (e.g., the 4-dof version of the Blue Workforce Ragnar). On the contrary, serial-parallel designs involve additional serial chains that can potentially be added or detached easily and in comparatively short times.

In this context, the following analyses distinguish between dimensional reconfiguration (corresponding to the notion of variable-dimension modules or geometry morphing) and functional reconfiguration (by adding or removing additional serial chains to the classical parallel Delta architecture). The practical implementation is respected but not shown in detail. Thus, it is not distinguished between static or dynamic reconfiguration. It should be noted that it is possible to detect new (dimensional and functional) configurations and automatically generate the related kinematic and dynamic models for control [21].

A. Dimensional Reconfiguration

The parallel architecture of the Delta robot includes three identical modules for the proximal links and three or six identical modules for the distal links and the connecting rods, respectively. Only a few approaches related to dimensional reconfiguration possibilities of the Delta robot can be found in literature.

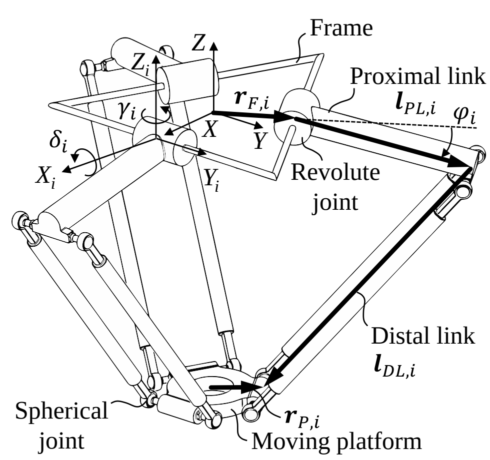

Fig. 1. Geometric relations and notations of the 3-dof Delta robot

In Miller's New University of Western Australia Robot (NUWAR) [22], the size and shape of the Delta workspace can be varied by changing the orientation of the motor axes with respect to the local horizontal axis X_i and/or to the local vertical axis Z_i (cf. Fig. 1).

Variation of the radius determining the actuator positions on the frame ($r_{F,i}$) and the link lengths ($l_{PL,i}$ and $l_{DL,i}$) are presented in [23]. Analyses include the influences of the reconfiguration of the said dimensions on the workspace size and shape as well as on payload capacities. Using ball screw drives as linear actuation, the frame radius can potentially be reconfigured symmetrically and dynamically during operation. Recent advances of the proposed design include vertical linear actuation in order to dynamically change the configuration of the frame radius and, additionally, adapt the relative height of the actuators to the frame [24].

Recently, in another interesting study [25], variable dimensions of the moving platform radius ($r_{P,i}$) are generated using Bricard's orthogonal 6R-linkage (i.e., an actuated closed overconstrained serial chain) to replace the rigid output link.

Other conceivable reconfiguration possibilities include asymmetric circular arrangement of the frame- and platform-related joints. In this study, symmetric arrangement with 120° is presumed. Similarly, the link lengths can be varied asymmetrically and other dimensions (e.g., radii and wall thickness) can be considered variable, which is not considered in this study. Table I summarizes the basic possibilities for symmetric dimensional reconfiguration.

B. Functional Reconfiguration

All industrial Delta robots can optionally be equipped with at least one additional rotational dof. Analyses of the portfolio of 18 manufacturers (including ABB, Adept, Bosch, Codian, FANUC, Kawasaki, and MAJAtronic) show that more than two thirds of the offered 4-dof models deploy the central telescopic shaft, and the rest a direct drive attached to the end-effector. Available 6-dof-concepts consist of the basic Delta structure and a 3-dof rotational head or serial robotic wrist (type RRR) mounted on the platform and driven by three separate motors fixed on the frame (e.g., FANUC's M-1 Series) or integrated into the parallelogram (e.g., FANUC's M-3 Series). These concepts are also offered with a single rotational dof. In other interesting designs (e.g., Yaskawa's patent [26]) the complete chain (i.e., proximal link and parallelogram) is used to transmit up to three additional rotational dof from the frame to the platform.

TABLE I
POSSIBILITIES FOR DIMENSIONAL RECONFIGURATION

Not.	Parameter description
$r_{F,i}$	Radius of the frame (denoting the related joint position)
δ_i	Orientation of the motor axis with respect to X_i
γ_i	Orientation of the motor axis with respect to Z_i
$l_{PL,i}$	Length of the proximal link
$l_{DL,i}$	Length of the distal link/connecting rod
$r_{P,i}$	Radius of the platform (denoting the related joint position)

TABLE II
POSSIBILITIES FOR FUNCTIONAL RECONFIGURATION

Not.	Parameter description
E_F	Wrist motor(s) attached to the frame
E_{PL}	Wrist motor(s) attached to the proximal link(s)
E_{DL}	Wrist motor(s) attached to the distal link(s)
E_P	Wrist motor(s) attached to the moving platform

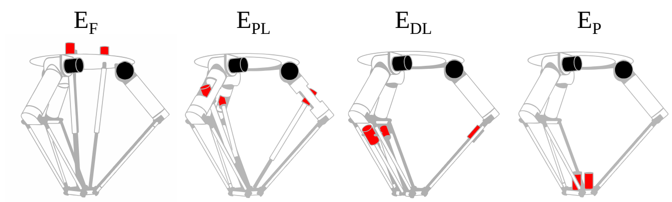

Fig. 2. Representation of functional reconfiguration possibilities (6-dof)

In recent years, 5-dof versions too can be observed in industry. For their D5 series, Codian Robotics applies the known solution with two additional RUPUR chains where the motors are attached to the frame. MAJAtronic GmbH holds a patent [27] for a special design of the telescopic shaft allowing for tool media supply. In their RL5 series, another telescopic shaft is guided through it. Thus, two coaxial telescopic shafts are applied to drive two additional rotational dof. Krones AG recently proposed a similar design but with coaxial linear and rotary actuators [28].

To sum up, four different functional reconfiguration possibilities can be identified. Depending on the desired rotational dof, one to three kinematic chains are used in order to attach the additional serial chains. The attachment point is given by the wrist motor position on the respective body of the basic parallel Delta robot. Table II and Fig. 2 summarize the resulting possibilities for a functional reconfiguration.

IV. METHODOLOGY

Efficient robotic systems are usually tailored to specific requirements of known production processes or handling tasks. The number of systems however is restricted due to limited factory areas and fixed costs. Imagine an assembly line with handling objects of great diversity (e.g., variable size or weight) resulting from highly fluctuating known order streams. Using mathematical optimization modeling and solution techniques, it is possible to identify (a given number of) p configurations from a set of reconfigurable handling systems such that the set of known objects is handled most efficiently. The optimized configurations will not be changed until the set of tasks is completed. Then, in order to efficiently handle a new set of tasks, each robot within a production line can be reconfigured. Mathematically, simultaneously selecting p configurations (from all possible) and assigning tasks to the selected ones resembles a standard problem in operations research, namely locating facilities for efficiently supplying demand locations. In this interpretation, p configurations are identified (*location*), each accomplishing a specific task from a given set of handling tasks (*allocation*). The set of reconfigurable handling systems is given by the basic Delta robot and a finite number of dimensional and functional reconfiguration possibilities, whereas market data is used to generate a set of potential handling tasks.

V. Model Formulation

Facility location problems, and the more relevant variant p-median problems [29], have several practical applications. Examples include, among others, the reduction of the trim loss in glass cutting industry [30], the optimal design of demand-related shipper and packaging sizes [31], [32], including a patent by Amazon Technologies [33], the optimization of production processes as cell formation problems [34], as well as cluster analyses [35]. The standard p-median problem can be formulated as a so-called integer program:

$$\Phi = min \sum_{k \in A} \sum_{j \in M} c_{kj} y_{kj} \quad (1)$$

such that

$$\sum_{j \in M} y_{kj} = 1 \qquad \forall k \in A \quad (2)$$

$$\sum_{j \in M} x_j = p \quad (3)$$

$$y_{kj} \le x_j \qquad \forall j \in M \quad (4)$$

$$x_j \in \{0,\ 1\} \qquad \forall j \in M \quad (5)$$

$$y_{kj} \in \{0,\ 1\} \qquad \forall k \in A, \forall j \in M \quad (6)$$

where M is the set of potential configurations (with $j = 1, \ldots, m$), A the set of handling tasks ($k = 1, \ldots, n$), c_{kj} the energy consumption (denoted as costs) of configuration j performing task k (V.C), whereas a penalty applies if configuration j cannot perform task k. Furthermore, the binary decision variables are denoted as $x_j = 1$ if configuration j applies (and zero otherwise) and $y_{kj} = 1$ if a task k is allocated to a configuration j (and zero otherwise). Constraint (2) ensures that each task k is allocated to a configuration j. By (3) the number of applied configurations is fixed to p. Finally, with (4) it is ensured that a task k can solely be allocated if configuration j selected. Market figures are used to generate the set of handling tasks (V.A). For defining the configuration space a fixed value discretization is used (V.B).

A. Demand-Related Handling Tasks

It is assumed that the demand-related handling tasks are characterized by the mass of the handling object, the size of the prescribed workspace, and the required dof. Market figures can be used as a basis for generating the set of handling task.

TABLE III
Shares of Payload, Workspace (WS) Diameter, and dof

Payload [kg]	Share [%]	WS-∅ [m]	Share [%]	dof [–]	Share [%]
0.1 - 3	62	0 - 0.4	5	3	33
3 - 6	18	0.4 - 0.8	23	4	52
6 - 9	4	0.8 - 1.2	40	5	7
9 - 12	4	1.2 - 1.6	31	6	8
12 - 20	12	1.6 - 2	1		

TABLE IV
Dimensional and Functional Configurations

$r_{F,i}$ [m]	$l_{PL,i}$ [m]	$l_{DL,i}$ [m]	Ext. [–]	dof [–]
0.2	0.200	0.5	E_F	3
0.3	0.275	0.6	E_{DL}	4
…	…	…	E_P	5
0.6	0.500	1.3	none	6

Accordingly, more than 150 commercial Delta variants were analyzed in respect of their payload, reachable workspace diameters, and dof. Table III summarizes the results. It can be seen that the payload of more than 80 % of commercially available models is not more than 6 kg. The diameter of the reachable workspace of more than 90 % of the variants is between 0.4 and 1.6 m. Finally, more than 80 % of the models offer three to four dof. From these figures a representative set of handling tasks is derived. The payload distribution is assumed to correspond to the distribution of object masses. For the workspace a fixed height of 0.3 m is presumed, where the largest workspace up to 2 m is ignored. Data need to be adjusted by currently unavailable process figures and actual product streams. In real application however, data can be extracted from current demand numbers or demand statistics.

For this study market figures are used to establish basic data (i.e., value ranges and distributions) from which then $n = 200$ tasks are generated to form set A.

B. Potential Configurations

Potential dimensional and functional configurations were introduced in Sec. III. Set M of potential configurations is generated combining discrete values for selected dimensions, types of extensions, and number of dof. For practical and symmetrical reasons, the orientations of the motor axes are set to zero, the platform radius is fixed to $r_{P,i} = 0.1$ m, and the theoretical functional extension E_{PL} is discarded. Then, combining all potential candidates following Table IV, $5 \cdot 5 \cdot 9 \cdot 4 \cdot 4 = 3{,}600$ configurations can be derived.

If a functional extension applies, the number of dof must be more than three. Thus, candidates without extension but more than three dof and, vice versa, candidates with extension but less than four dof are discarded. This finally results in $m = 2{,}250$ potential configurations. Note that model (1-6) is able to optimally select (and simultaneously optimally assign tasks) from the entire feasible configuration space.

C. Performance Measure

The energy consumption serves as performance indicator to assess the allocation of task k to configuration j. Accordingly, performance trajectories need to be taken into account.

The paths are defined in accordance with the required workspace size and for higher variance of the indicators randomly rotated about the vertical axis in steps of $\pi/6$ (cf. Fig. 3). Depending on the path geometry, times are set so that industrially-relevant motions similar to [36] arise. The relative position of the prescribed workspace and the related trajectory to the origin of the frame in Z-direction is assumed to be the median of all valid relative positions identified by preliminary kinematic analyses.

The kinematic and dynamic modeling of functionally extended Delta robots is presented in [37]. The functional reconfiguration possibilities are solely analyzed in respect of their influences on the actuation torques of the basic parallel structure of the Delta robot. Thus, the masses and mass moments of inertia are adapted according to the dimensional reconfiguration possibilities. The masses of the proximal and distal links are adapted by a linear scale factor

$$C_{ij} = l_{ij}/l_{i0} \tag{7}$$

i.e., the ratio of the length of link i in configuration j and the corresponding original value based on real robot data denoted by zero (as provided in [37]). The connecting rods are modeled as thin rods. Thus, as a simplification, the mass moment of inertia (about the perpendicular axes) I at the center of a connecting rod of the distal link is adapted by

$$C_{DL,ij,I} = \left(l_{DL,ij}/l_{DL,i0}\right)^3 \tag{8}$$

Due to a more complex topology of the proximal link, its mass moment of inertia follows a more complicated definition which, even in a simplified case, additionally depends on radii. Thus, the properties of different links as used in real systems are compared. Accordingly, the mass moment of inertia of the proximal link can be approximated by the quadratic relation

$$C_{PL,ij,I} = \left(l_{PL,ij}/l_{PL,i0}\right)^2 \tag{9}$$

The torques τ_i of the three main drives can finally be derived solving the inverse dynamics problem. Then the average energy consumption of a configuration j performing a task k is given as [37]:

$$E_{kj} = c_{kj} = \tfrac{1}{3}\sum_i \int_0^T max\left(\tau_{kji}\dot{\varphi}_{1kji}, 0\right) \cdot dt \tag{10}$$

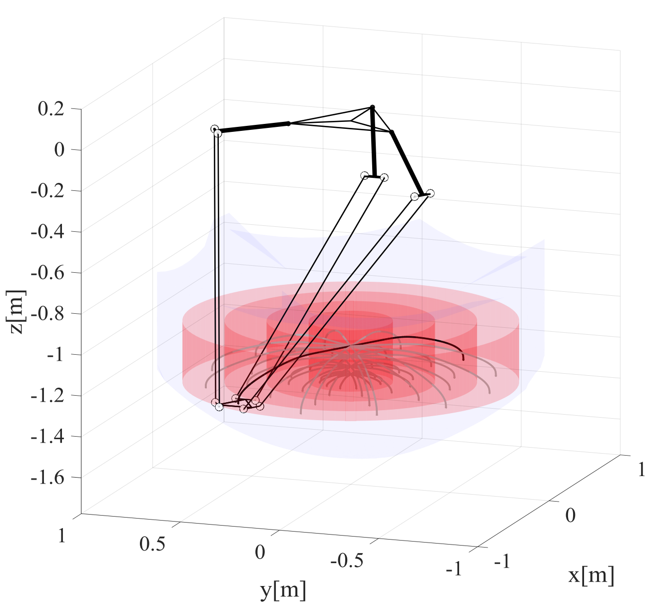

Fig. 3. Performance trajectories within the prescribed workspaces

where $\dot{\varphi}_{1kji}$ denotes the actuation velocity. Here, it is assumed that the braking energy cannot be recuperated. Thus, in order to optimize (1), $n \cdot m = 450{,}000$ cost values c_{kj} need to be computed. Therefore, efficient analytical dynamic modeling approaches are essential. A comparison study of six models in [37] (based on Newton-Euler, the principle of Virtual Work, the Lagrangian formulation, Kane's equations, a natural orthogonal complement, and Hamilton), including validation with real experiments, showed that the Lagrangian formulation is most efficient for E_{DL} and E_P. Additional serial chains involving relative motions of the telescopic shafts however lead to cumbersome partial derivatives and comparatively high computation times. Alternatively, Kane's formulation [38] can be applied to compute the actuation torques and energy consumption of E_F more efficiently.

For each of the q rigid bodies of the (functionally extended) Delta robot, the sum of generalized applied and inertia forces and moments ($\boldsymbol{W}$ and $\boldsymbol{W}^*$) is zero. For the three generalized coordinates φ_{1i}, Kane's equations are then given as:

$$\boldsymbol{W} + \boldsymbol{W}^* = \boldsymbol{V} \cdot (\boldsymbol{F} + \boldsymbol{F}^*) + \boldsymbol{\Omega} \cdot (\boldsymbol{M} + \boldsymbol{M}^*) = \boldsymbol{0_3} \tag{11}$$

with $\boldsymbol{F}$ and $\boldsymbol{F}^*$ ($\boldsymbol{M}$ and $\boldsymbol{M}^*$) as $(3q \times 1)$-vectors containing the resultant applied and inertial forces (moments) for each rigid body of the system and $\boldsymbol{V}$ and $\boldsymbol{\Omega}$ as $(3 \times 3q)$-matrices containing the partial derivatives of the linear and angular velocities, respectively, according to the generalized coordinates. The actuation torques can then be extracted solving (11) for the applied moments $\boldsymbol{M}$. For the sake of brevity, a detailed derivation of the Kane model of functionally extended Delta robots is left to be addressed in further reports.

Each combination of handling task and configuration is analyzed in respect of the resulting energy consumption. The resulting $(n \times m)$-cost matrix can then be transferred to the p-median formulation (1-6) and solved to obtain the optimal allocations. Fig. 4 summarizes the overall approach.

VI. Analysis and Results

The test instance includes $n = 200$ handling tasks and $m = 2{,}250$ configurations. At this stage, set-up times and costs as well as capacity and occupancy figures are not considered in order to demonstrate general feasibility of the approach. Thus, allocations are unconstrained unless the imposed trajectory cannot be reached.

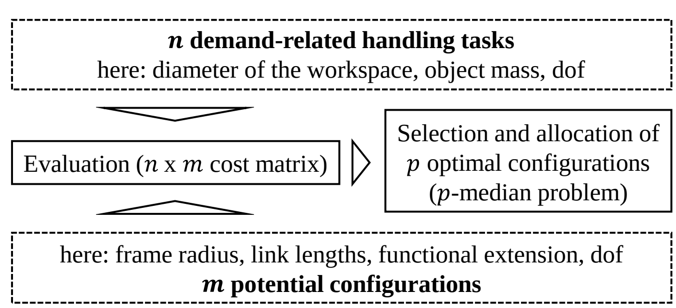

Fig. 4. Optimized reconfiguration planning using a p-median approach

TABLE V
OPTIMAL CONFIGURATIONS FOR $p = 6$

$p = 6$	Conf. 1	Conf. 2	Conf. 3	Conf. 4	Conf. 5	Conf. 6
$r_{F,i}$ [m]	0.2	0.3	0.2	0.3	0.4	0.3
$l_{PL,i}$ [m]	0.2	0.275	0.275	0.35	0.425	0.35
$l_{DL,i}$ [m]	1.1	1.3	1	1.3	1.3	1.3
Ext. [–]	E_F	E_F	E_F	–	E_F	E_F
dof [–]	4	4	6	3	4	6
WS-∅ [m]	0.8	1.2	1.2	1.6	1.6	1.6
Cvg. [%]	22	33.5	9.5	13.5	16	6

The energy consumption of each allocation serves as cost function whereas costs for installation and reconfiguration are neglected. In case a trajectory cannot be reached, a penalty applies for the related cost value (cf. Sect. V). The kinematic and dynamic models were implemented in MATLAB® and validated with real experiments as shown in a previous study [37]. For the underlying mass parameters it is referred to [36]. With this $n \cdot m$ cost values were computed. The p-median problem was implemented in its standard formulation using Python™ and then solved with Gurobi Optimizer.

In automation industry a production line is usually equipped with five to seven Delta robots. In this case study, the production line is optimized using six configurations. Accordingly, from 2,250 reconfiguration possibilities, six configurations are selected and optimally allocated to 200 known tasks. After a certain period, the robots may be reconfigured based on new process data and product streams.

Table V summarizes the optimal solutions for a production line with maximal $p = 6$ configurations. It can be seen that each configuration covers at least 6 % of all tasks and at maximum 33.5 %. Since energy efficiency is used as target value, the lengths of the light-weight distal links reach maximum values for four of the six selected configurations and all extensions are related to the frame (i.e., E_F) in order to minimize the inertial effects of the additional bodies.

Tasks in which workspaces of 1.2 m and 1.6 m need to be reached are each served by configurations with equal proximal links except for configuration 5. It shows a larger dimension for the proximal links potentially resulting from the underlying 4-dof trajectories which imposes higher demands on the robot than those served by configurations 4 and 6. Then, the inertial effects of the functional extensions on the actuation torques are smaller and thus, less energy consumption of the main drives is observed. Interestingly, all tasks requiring 5-dof are served by the 6-dof variants. In order to increase efficiency of the overall production line, a 4-dof variant with minimal proximal links is selected to perform tasks with workspaces of 0.8 m and less.

To assess the potential energy saving, the total energy consumption of the six different optimal configurations is compared to the energy consumption of a production line with six identical configurations each covering all tasks. Among all potential configurations, configuration 6 of the optimal solution set covers all tasks. By allocating the tasks according to the optimal solution, energy consumption is effectively reduced by 11.8 % compared to allocating all tasks to configuration 6.

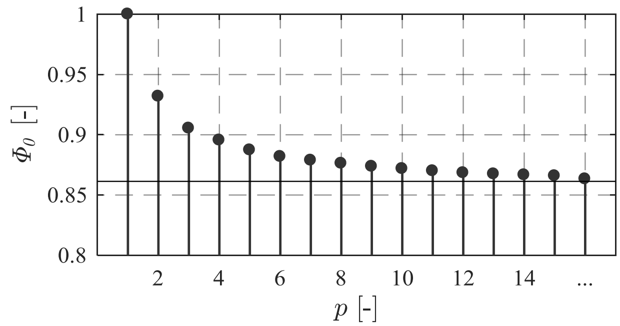

Fig. 5. Normalized total energy consumption Φ_0 depending on the number of configurations p

Compared to the worst configuration covering all tasks, drastic reductions of 63.2 % can be achieved.

Compared to the optimal solution for $p = 6$, further reductions can be achieved allowing a higher number of configurations within the production line. Emphasizing the consistency of the approach, Fig. 5 displays the normalized total energy consumption Φ_0 related to the number of configurations p (cf. (3)). Accordingly, applying two optimal configurations instead of one (i.e. configuration 6), the total energy consumption drops by 6.9 %. Then, the energy consumption degressively decreases reaching a threshold of 0.861 (corresponding to 13.9 % energy saving) for $p > 15$.

VII. DISCUSSION AND OUTLOOK

This paper presented a novel and rigorous approach for the optimization of the reconfiguration planning. Results showed that operations research techniques can effectively be applied to reduce the energy consumption of reconfigurable production systems. The approach is robust in the sense that it can easily accommodate a number of future extensions and different data. The key advantage of the approach is that it can be repeated regularly in order to counter the increasing complexity of handling tasks stemming from the ever-growing demand for automation. The underlying handling tasks of this case study were generated using market figures and thus, are limited to 200 tasks. Future investigations will focus on larger data sets ideally gathered from real process data. For defining the configuration space we used a fixed value discretization, cf. Table IV. It should be evaluated in a sensitivity analysis whether it pays to work with a finer discretization. In a solution process, it could be dynamically adapted as needed. The total energy consumption was used as target value for optimization. Computation times for the cost matrix are very high even though efficient dynamic modeling techniques were introduced. The two latter aspects advocate for a different modeling and more elaborate solution technique known as column generation. This allows for handling an even larger configuration space while still guaranteeing an optimal selection and task allocation. It should however be noted that since a production system is only reconfigured after a certain period of time, even currently high computational costs can be considered acceptable. Kinematic performance measures (e.g., motion and force transmission factors or the installation space) can be considered as alternative optimization targets or as additional constraints. From the economic point of view, initial procurement and operating costs need to be taken into account. Moreover, set-up times and costs as well as capacity and occupancy figures need to be addressed for industrial application. Such figures can for instance be taken into account extending the proposed model to a capacitated p-median problem including fixed (facility opening) costs.

REFERENCES

[1] Multi-Annual Roadmap (MAR) for Horizon 2020, SPARC Robotics, euRobotics AISBL, Brussels, 2017.

[2] V. E. Gough, "Contribution to discussion of papers on research in automobile stability, control and tyre performance," in *Proc. of the Inst. of Mechanical Engineers, Automobile Division*, 1956, pp. 392–394.

[3] D. Stewart, "A Platform with Six Degrees of Freedom," in *Proc. of the Institution of Mechanical Engineers*, vol. 180, no. 1, 1965, pp. 371–386.

[4] J. Brinker and B. Corves, "A Survey on Parallel Robots with Delta-like Architecture," in *Proc. 14th World Congress in Mechanism and Machine Science*, Taipei, Oct. 2015.

[5] R. Clavel, "Conception d'un robot parallèle rapidé à 4 degrés de liberté", Ph. D. thesis, EPFL, Lausanne, 1991.

[6] A. Siddiqi and O. L. de Weck, "Modeling Methods and Conceptual Design Principles for Reconfigurable Systems," *J. Mech. Des*, vol. 130, no. 10, 101102, 2008, 15 pages.

[7] M.G. Mehrabi, A. G. Ulsoy, and Y. Koren, "Reconfigurable Manufacturing Systems Key to Future Manufacturing," *J. of Int. Manufacturing*, vol. 11, no. 4, 2000, pp. 403–419.

[8] R. M. Setchi and N. Lagos, "Reconfigurability and reconfigurable manufacturing systems state-of-the-art review," in *Proc. of the IEEE Int. Conf. on Industrial Informatics*, Berlin, June 2004.

[9] A. Kumar Dash, I-M. Chen, S. H. Yeo, and G. Yang, "Task-oriented configuration design for reconfigurable parallel manipulator systems," *Int. J. of Computer Int. Manuf.*, vol. 18, no. 7, 2005, pp. 615–634.

[10] M. Krefft, "Aufgabenangepasste Optimierung von Parallelstrukturen für Maschinen in der Produktionstechnik," Diss., TU Braunschweig, 2006.

[11] T. Mannheim, M. Riedel, M. Hüsing, and B. Corves, "A New Way of Grasping PARAGRIP – The Fusion of Gripper and Robot," *Mechanisms and Machine Science: Grasping in Robotics*, vol. 10, 2012, pp. 433–464.

[12] F. Xi, Y. Li, and H. Wang, "A Module-based method for design and analysis of reconfigurable parallel robots," in *Proc. of the IEEE ICMA*, Xi'an, August, 2010.

[13] A. Moosavian and J. Xi, "Design and analysis of reconfigurable parallel robots with enhanced stiffness," *Mechanism and Machine Theory*, vol. 77, 2014, pp. 92–110.

[14] Y. Jin, B. Lian, M. Price, T. Sun, and Y. Song, "QrPara: A New Reconfigurable Parallel Manipulator with 5-Axis Capability," *Mechanisms and Machine Science: Advances in Reconfigurable Mechanisms and Robots II*, vol. 36, 2015, pp. 247–258.

[15] X. Kong, J. Yu, and D. Li, "Reconfiguration analysis of a 2-dof 3-4R parallel manipulator with planar base and platform," in *Proc. of the ASME IDETC/CIE 2015*, Boston, August 2015.

[16] J. D. Arena and J. T. Allison, "Solving the Reconfigurable Design Problem for Multiability with Application to Robotic Systems," in *Proc. of the ASME IDETC/CIE 2014*, Buffalo, August 2014.

[17] A. D. Finistauri and F. Xi, "Reconfiguration Analysis of a Fully Reconfigurable Parallel Robot," *J. Mechanisms Robotics*, vol. 5, no. 4, 041002, 2013, 18 pages.

[18] W. Ye, Y. Fang, and S. Guo, "Reconfigurable Parallel Mechanisms with Three Types of Kinematotropic Chains," in *Proc. 14th World Congress in Mechanism and Machine Science*, Taipei, Oct. 2015.

[19] N. Plitea, D.-B. Lese, D. Pisla, and C. Vaida, "Structural design and kinematics of a new parallel reconfigurable robot" *Robotics and Computer-Integrated Manuf.*, vol. 29, no. 1, 2013, pp. 219–235.

[20] J. Schmitt, D. Inkermann, C. Stechert, A. Raatz, and T. Vietor, "Requirement Oriented Reconfiguration of Parallel Robotic Systems," in *Robotic Sy. – App., Control and Programming*, 2012, pp. 387–410.

[21] A. D. Finistauri, F. Xi, and B. Petz, "Architecture Design and Optimization of an On-the-Fly Reconfigurable Parallel Robot," in *Parallel Manipulators, towards New Applications*, 2008, pp. 379–404.

[22] K. Miller, "Synthesis of a manipulator of the new UWA robot," in *Proc. of Austr. Conf. on Robotics and Autom.*, Brisbane, 1999, pp. 228–233.

[23] M. Maya, E. Castillo, A. Lomelí, E. González-Galván, and A. Cárdenas, "Workspace and Payload-Capacity of a New Reconfigurable Delta Parallel Robot," *Int. J. Adv. Robotic Sy*., vol. 10, no. 56, 2013, 11 pages.

[24] A. L. Balmaceda-Santamaría, E. Castillo-Castaneda, and J. Gallardo-Alvarado, "A Novel Reconfiguration Strategy of a Delta-type Parallel Manipulator," *Int. J. Adv. Robotic Sy*., vol. 13, no. 15, 2016, 11 pages.

[25] M. Pfurner, "Analysis of a Delta Like Parallel Mechanism with an Overconstrained Serial Chain as Platform," in *Proc. 14th World Congress in Mechanism and Machine Science*, Taipei, Oct. 2015.

[26] W. Zhang and H. Nakamura, "Parallel mechanism," U.S. Patent, 20130142608 A1, Kabushiki Kaisha Yaskawa Denki, June 6, 2013.

[27] H. Ilch, "Parallel robot," U.S. Patent, 9370867 B2, Majatronic GmbH, June 21, 2016.

[28] Hans Luber, Kurt Perl, Michael Hartl, and Stefan Elsperger, "Device for handling items and a method for operating such a device," European Patent, 2813328 A2, Krones Aktiengesellschaft, Dec. 17, 2014.

[29] H. Eiselt and V. Marianov, "Foundations of location analysis," *Int. Ser. in Oper. Res. and Manage. Sci.*, vol. 155, Springer, US.

[30] C. Arbib and F. Marinelli, "An optimization model for trim loss minimization in an automotive glass plant," *Eur. J. Oper. Res.*, vol. 183, no. 3, 2007, pp. 1421–1432.

[31] K. Dowsland, E. Soubeiga, and E. Burke, "A simulated annealing based hyperheuristic for determining shipper sizes for storage and transportation," *Eur. J. Oper. Res.*, vol. 179, no. 3, 2007, pp. 759–774.

[32] J. Brinker and H. I. Gündüz, "Optimization of demand-related packaging sizes using a p-median approach," *Int. J. Adv. Manuf. Tech.*, vol. 83, 2016, 10 pages.

[33] H. Tian, M. Smith, and D. Mishra, "Optimization of packaging sizes," U.S. Patent, 8340812, Amazon Technologies, Inc., Dec. 25, 2012.

[34] Y. Won and K. Lee, "Modified p-median approach for efficient GT cell formation," *Comput. Ind. Eng*., vol. 46, no. 3, 2004, pp. 495–510.

[35] H. Köhn, D. Steinley, and M. Brusco, "The p-median model as a tool for clustering psychological data," *Psychol. Methods*, vol. 15, no. 1, 2010, pp. 87–95.

[36] J. Brinker, B. Corves, and M. Wahle, "A Comparative Study of Inverse Dynamics based on Clavel's Delta robot," in *Proc. 14th World Congress in Mechanism and Machine Science*, Taipei, Oct. 2015.

[37] J. Brinker, N. Funk, P. Ingenlath, Y. Takeda, and B. Corves, "Comparative Study of Serial-Parallel Delta Robots with Full Orientation Capabilities," *IEEE Robotics and Automation Letters*, 2017, additionally selected by ICRA'17 Program Committee for presentation at the conference.

[38] T. R. Kane and D. A. Levinson, "The use of Kane's dynamical equations for robotics," *Int. J. Robot. Res.*, vol. 2, 1983, pp. 3–21.