Precision Assembly of Optical Backplanes

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Abstract.
Full optical backplanes can be seen as a promising technology for high bandwidth ICT (Information and Communication Technology) apparatuses and high performance computing systems. According to a recent frame-based solution, the backplane mounts a number of independent optical interconnect circuits mainly consisting of a set of optical fiber ribbons of different lengths arranged to fulfill a specific planar ribbon routing. A non-negligible problem is related to the development of suitable techniques for the efficient and cost-effective assembly of such sub-circuits. New systems are required that combine ultimate hardware and software capabilities and derive from a synergic implementation of digital and advanced manufacturing technologies. The successful assembly of the optical interconnection circuits lies in the development of cyber-physical production systems within the framework of Industry 4.0. In this context, this work will present and discuss how different innovative technologies and consolidated technologies applied in a novel context were exploited to demonstrate the feasibility of the automated backplane assembly. The achieved results are discussed in terms of design of the work-cell layout and related equipment, simulation tests, tool path planning, and final task execution.

Keywords: Optical Backplane, Robotic Assembly, Cyber-Physical Work-cell.

1 Introduction

The manufacturing industry is going through the fourth industrial revolution where the physical world is coupled with the cyber world mainly exploited for design, simulation, monitoring, computing, and networking purposes. These cyber-physical systems contribute to the efficiency, sustainability, and security of production systems. The key technologies enabling such a revolution include both hardware and software resources, from advanced robotic systems to additive manufacturing, up to cloud computing and system simulation.

Recent considerable improvements in robotics are offering advanced robotic solutions with reduced labor costs and increased efficiency. Advanced robotics is introducing a new generation of machines capable of executing dexterous and delicate tasks, such as recognizing, computing and acting on information, and even collaborating and learning from humans [1].

A fundamental goal of this emerging new industrial paradigm is to develop autonomous production methods, plants and factories powered by robots that can execute different tasks smartly, with the focus on safety, flexibility, versatility, and collaboration. Without the need to isolate its working area, its integration into human workspaces becomes more economical and productive, and opens up many possible applications in industries, with robots and humans working hand in hand on interlinking tasks and using smart sensors and human-machine interfaces [2]. The cognitive aspects in an advanced robotic system are important for its context awareness. Smart sensors, as on-board vision systems or optical sensors, allow the robots to measure the object distance and attain 3D coordinates with high precision, e.g. by sophisticated image recognition methods. Moreover, the robot control strategy plays a fundamental role in the achievement of smart, robust and versatile behavior of a robotic system. For example, the adoption of hybrid force-motion control, as well as indirect force control, allows for the execution of interactive tasks where it is more important to precisely control and limit the exchanged force/torque by the robot, rather than to control the robot position or its path. Robots using force, tactile, distance, and visual feedback can operate in unstructured environments, cooperating safely with the human to perform different tasks.

The paper discusses the development of a robotized work-cell for the automatic assembly of an optical backplane for high-bandwidth ICT apparatus, to be integrated in a production line implementing the concepts of digital manufacturing. After a brief overview of the apparatus, the technologies enabling the Industry 4.0 concepts are reviewed and their (successful) application to the use case is critically addressed.

2 Backplane design and assembly challenges

2.1 Optical backplane for ICT apparatus

High-effectiveness optical connections are requested in high-bandwidth ICT apparatus (data centers, servers, routers, switching stations, etc.) and high-performance computing systems [3] to overcome the limits of traditionally used electrical PCBs, in terms of power dissipation and data transmission capacity. These devices are based on optical backplanes where a plurality of cards are connected to each other with optical interconnection circuits, allowing signal transmission between cards on the backplane. In recent years several solutions have been proposed for optical backplane interconnection circuits [4, 5].

The novel backplane design considered in this paper and better described in [6, 7, 8] features a “full-mesh” topology: each card can transmit data to any other card or be connected to itself, i.e. loop-back connection. This specific design allows for the division of the backplane optical circuit into n independent optical interconnection subcircuits, each with different ribbon routing and encapsulated into a different rigid frame.

The main components of each sub-circuit (Fig. 1) are: a frame support, a frame cover, eight 12 core multimode (MM) ribbons each with two terminations (MPO connectors and MT ferules), 16 ribbon termination housings.

The interconnection solution is based on controlled deformations of the optical fiber ribbons, using an optimized layout and customized components as fibers support and protection (frame). These frames have been designed with mechanical features (i.e.: pins, boundary walls) to constrain the ribbons in an optimized position which minimizes optical power losses. The entire routing is thus planarly developed on the backplane surface, exploiting a customized parametric algorithm [7].

A non-negligible effort is required in order to develop a fully automated solution for the efficient and cost-effective assembly of full optical backplanes combining the flexibility of a robotic cell with customized assembly tools. Indeed, the novelty of such products called for new methods and systems to enable their development. It required transversal competencies and a synergic integration of different engineering disciplines, boosted by digital and advanced manufacturing. The technologies behind the successful assembly of the optical interconnection circuits could be then identified within the framework of Industry 4.0, towards the development of a cyber-physical production system.

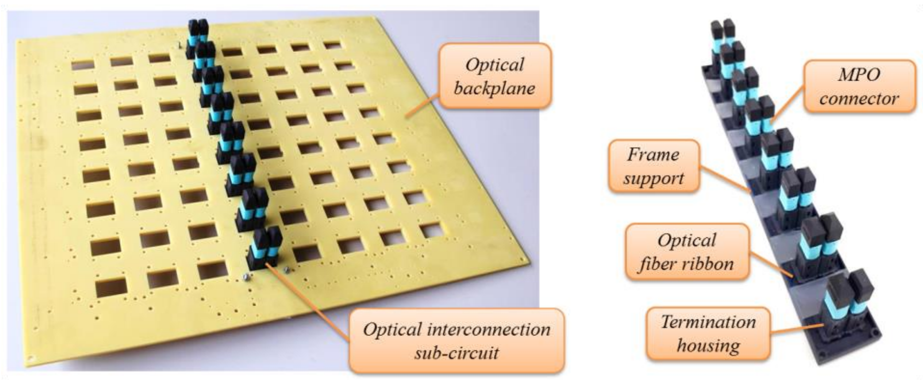

Fig. 1. Backplane optical interconnection sub-circuit.

2.2 Assembly strategy and main steps

The backplane assembly features many challenges, which can be summarized as follows:

1. The flexibility of the optical fiber ribbons implies their unpredictable and undefined behavior.
2. Ribbon length varies: different connector couples, at different distance, have to be connected and the ribbons have to be managed.
3. *N* different (predefined optimized) routings have to be implemented.
4. Objects with different geometrical and mechanical properties (ribbons, connectors, mechanical customized components, frames) have to be handled and assembled.
5. Positioning requires high accuracy and repeatability.

Fully automatized assembly technologies, based on vision systems, robotics, and industrial automation devices can be used for the circuit assembly.

Firstly, the main phases of the assembly process were identified and detailed:

1. Delivery of the commercial ribbon in the workspace with the ferrules and the connectors at both ends.
2. Mounting of the termination housings on both ribbon ends.
3. Pick of the pre-headed ribbon with termination housings from the specific storage buffer.
4. Insertion of the termination housings in the proper receptacles on the assembly tool, according to the topology of the interconnection sub-circuit.
5. Repetition of steps 2-4 for each ribbon of the sub-circuit in process.
6. Sliding of the assembly tool to align the receptacles in a straight line.
7. Pick of the frame from a storage buffer.
8. Positioning of the frame over the aligned termination housings.
9. Snap of the frame on the line to transfer the ribbons.
10. Pick of the circuit (frame with transferred ribbons) and warehousing.
11. Repetition of steps 2-10 for all the circuits of the backplane.

It has to be noted that, analyzing the process, steps 5 and 6 could be not consequent, but specific ribbons could be placed and inserted after the alignment of the receptacles on the assembly tool. This would reduce the need of longer ribbons to handle the distances between the receptacles on the assembly tool.

3 Automatic assembly: Enabling technologies

A high-performance work-cell resulted from the exploitation of Industry 4.0 principles. Indeed, the requirements of the work-station were flexibility, reconfigurability and safety. This includes the work-cell layout, its specialized stations to execute specific operations, all the devices and modules for handling and assembling the different components, as well as the components themselves, both those constituting the interconnect sub-circuit (re-design for assembly) and the auxiliary equipment and elements necessary for a correct assembly. In the following, the enabling technologies of Industry 4.0 exploited to develop an automated backplane assembly method and work-cell will be discussed.

3.1 Robotized assembly solution

The work-cell was equipped with a robot with smart sensors and advanced control strategies. The work-station was designed according to a circular layout where an anthropomorphic robot is at the center and the assembly sub-stations are arranged around it. In this way, the robot can reach all the sub-stations in order to support all the phases of the assembly process. Therefore, the robot tasks are many: manipulate the sub-components and the sub-circuit of the backplane, load and unload the components from the different sub-stations, and check all the assembly phases to guarantee the high assembly standard demanded. The sub-stations were designed for the specific sub-assembly tasks, as can be seen in Fig. 2. In particular, the robot has to assemble the circuit placing the ribbons on the tool according to the TX/RX optical ribbon path. Then, the termination housings have to be aligned on the assembly tool by pneumatic actuation and finally the robot has to snap the frame on the line.

The work-cell was equipped with a highly precise compact 6 DOF anthropomorphic robot (see Fig. 2 for technical data). A 6 DOF force sensor, directly connected to the bottom part of the TCP flange allows for the implementation of force control, besides the standard motion control. Indeed, the robot has to perform tasks where the final goal is to reach defined positions following specific paths and adopting a velocity/position (motion) control strategy, but it also has to perform snap operations between the frame and the line of termination housings where it is necessary to control the force, adopting a hybrid force-motion control strategy. When this strategy is used, the robot is positioned over the first contact point of the frame, the z-axis is force controlled limiting the force to 60 N (maximum pushing force), while the x and y-axes are motion controlled. The robot is then moved downwards to the contact point and, once the contact is established, the robot pushes until the maximum pushing force is achieved. In case the maximum force is not achieved, a threshold height is set to avoid the task getting stuck. The robot then moves upwards and the previous operations are repeated for all the contact points defined on the frame surface to guarantee the complete snap with the terminations housings. These features make the system suitable for complex assembly tasks, such as the backplane assembly.

The robot end-effector was designed coupling two commercial pneumatic grippers by an angular interface. The two grippers were equipped with designed fingers able to manipulate the different components (i.e. the ribbon acting on the termination housing and the frame) and handle the optical ribbon path according to the specific sub-circuit topology. Each termination housing of the same ribbon was picked and inserted by each gripper, while the frame was picked, positioned, and pushed on the line of the aligned termination housings by only one of the grippers.

The robot is equipped with a 2D vision system consisting of a mobile camera mounted on the gripper interface. It is used to identify the components (i.e. the termination housings and the receptacles) by different search and match algorithms (i.e. pattern matching, geometric matching, particle analysis), measure their planar pose, and then identify the pick and release poses to be reached by the tool tip during the sub-circuit assembly in order to perform a look and move control strategy. Moreover, the vision system was used to check the effectiveness of the assembly phases in all the sub-stations. A diffuse illumination of the scene was used to assure a robust recognition and reliable measurement of the parts.

The vision system and the robot were calibrated to allow the automatic identification of the parts in the robot reference system for the grasp and the release. Indeed, a calibration algorithm was implemented to calibrate the work-cell, compensating for perspective, distortion, spatial referencing and end-effector errors.

In order to control the work-cell and the different devices (i.e. robot, end-effector, vision system, and tools) for the execution of the sub-circuit assembly tasks, a dedicated control system was designed and implemented.

This control system, implemented in NI LabVIEW©, provides simple tools for the scheduling of the operations to be performed in the work-cell and for the supervision of the automatic task during its execution; manages and supervises the execution of the defined task, sending commands to the various devices involved and making decisions based on their responses; supervises the system and manages the alarms. The control system integrates an HMI both for the automatic task and manual control of the different devices. Finally, the control system also allows for communication with external systems via TCP/IP protocol, e.g. for the remote control and data exchange in the case of integration of the work-cell in a production plant.

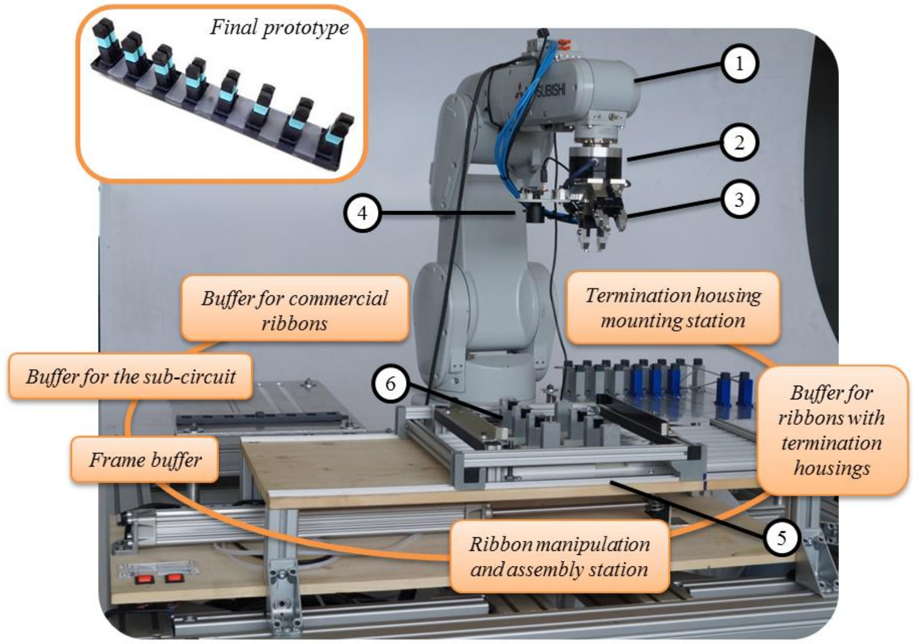

Fig. 2. The assembly work-cell. 1) Mitsubishi Melfa RV-4FL robot: position repeatability of ±20 µm; operating volume (hollow sphere) with outer radius of 648.7 mm); maximum load capacity of 4 kg; end-effector maximum x-y-z composite speed of 9048 mm/s; cycle time of 0.36 s for a back-and-forth movement over a vertical distance of 25 mm and a horizontal distance of 300 mm when the load is 1 kg. 2) 6 DOF Mitsubishi 1F-FS001-W200 force sensor: rated load of 200 N for F_x, F_y, F_z and of 4 Nm for M_x, M_y, M_z; maximum static load of 1000N for F_x, F_y, F_z and of 6 Nm for M_x, M_y, M_z; breaking load of 10000 N for F_x, F_y, F_z and of 300 Nm for M_x, M_y, M_z; resolution of approx. 0.03 N for F_x, F_y, F_z and of approx. 0.0006 Nm for M_x, M_y, M_z; linearity of 3% FS; hysteresis of 5% FS. 3) End-effector: two Schunk MPG40-plus grippers: stroke of 6 mm; repeatability of 0.02 mm; mass of 0.36 kg; maximum manipulation mass of 0.7 kg; maximum closing force less than 50 N (maximum value to avoid the damage of the components) with a command pressure of about 2 bar. 4) 2D vision system: 5 MPixel sensor; focal length of 10 mm; field of view of 155x116 mm^2; spatial resolution of 55 µm; working distance of 220 mm. 5) Customized assembly tool. 6) Receptacle on the assembly tool.

3.2 Digital work-cell design

The design spanned different levels, from the overall system perspective to the detailed features of the single component, taking into account the mutual effects of a design choice on those considered consolidated solutions and on the subsequent ones. In this way, the possibilities of the virtual prototyping were exploited to rapidly investigate multiple system changes and facilitate layout and task planning.

In addition to the work-cell main components (robot, work-stations and assembly tools), virtual prototypes were created for the buffer of ribbons with termination housings, the ribbon manipulation and assembly station, the frame buffer, and the buffer for the complete interconnection sub-circuit, as well as the manipulation tool on the robot end-effector. A set of receptacles were designed to support and make available for picking all the ribbons required for the production of the specific interconnection sub-circuit and the related ribbon routings.

The assembly work-cell was developed immediately after the first backplane components conception; several iterations were carried out in order to achieve a fully automated solution, re-designing the components of the interconnect sub-circuit and integrating additional elements on the assembly tool. This required a continuous verification of the feasible integration of the various parts of the system but allowed us to solve critical aspects that arose during the development stages.

The design modifications required a downstream verification of both the maximum allowable gripping force on the termination housing to avoid its damaging and the maximum allowable push force to snap the frame onto the aligned termination housings. Therefore, a FEM analysis was carried out using SolidWorks© and compared with the first FEM analysis performed during the original design. The results were comparable showing that the termination housing mechanical resistance was not negatively affected by the modifications, thus validating the new design. Thanks to a synergic second-stage development of the components and development of the automation devices, the frame also passed through a re-design to avoid the need for a gripper for the frame different from those used to manipulate the termination housings, therefore for a gripper change and changing system. The double-gripper solution was conceived and modeled using Solidworks. The grippers were equipped with custom fingers with multiple original features. The fingers should meet a wide set of specifications, that is those deriving from the components to manipulate (e.g. size, shape, surface for gripping, applicable forces), from the gripper (e.g. connection, size, mass), and from the assembly operations (e.g. avoiding interference with ribbons and other components).

Besides the components, an intervention on the original assembly tool was required. Indeed, to achieve a correct positioning in the layer of the assembly tool, the flexible part between the termination housings had to be controlled. For this reasons, additional retaining brackets on the assembly tool to constrain the ribbons within the desired space were added and auxiliary elements were created both on the receptacles and on the retaining brackets to support the ribbons then keep them at the proper height.

3.3 Additive technologies for components' manufacturing

A prototype of the work-cell was developed and installed at the Laboratory of Micro Robotics at ITIA, Milan. The different components of the interconnection sub-circuit and of the devices for the assembly were developed considering the most convenient manufacturing technologies. Additive manufacturing represented a promising solution in different cases, thanks to the possibility of obtaining highly customized products with different shapes and sizes, since they do not suffer from many of the geometrical limits constraining subtractive and formative processes, in small quantities at a relatively low cost per unit and in a short time. Moreover, the combination with digital technologies enabled and widened the fabrication possibilities.

In the work-cell, different components were developed by means of additive manufacturing technologies. The different releases of the termination housings, the frame, and the receptacles and their fixturing elements on the slides were produced by stereolithography. They were made of the Accura XTreme Plastic resin which simulates the properties of ABS. Part of the side fixturing for the on-board camera was manufactured by Fuse Deposition Modelling (FDM) process in ABS.

3.4 Virtual simulation and off-line programming

Numerous simulation tests were carried out using Melfa Works, an add-on for SolidWorks released by Mitsubishi. It converts the paths for the process in output data that can then be used for the creation of the robot program by the Mitsubishi software RT-ToolBox2. With Melfa Works, it is possible to select grippers, sensors and other components from libraries and integrate them directly in the environment [9]. The main phases of the simulation process included: the creation of the workspace, the calibration in the virtual environment, and the creation of the workflow. In more detail, the simulation environment allowed us to:

- load the model of the robot and define its settings;
- connect the gripper model;
- load and change the layout of all the devices (a functional simplified model of the devices was often used) in the work-cell assembly model, as well as the processing parts;
- teach the robot all the working positions (and intermediate configurations) to reach, as well as those for the calibration;
- check possible interference among robot and devices;
- create the sequence of the necessary operations to define the path.

4 Work-cell and interconnect circuit prototypes

The work-cell was tested in the assembly of one of the eight interconnect sub-circuits, i.e. the +2 routing, that was considered challenging from both the functionality of the circuit and the automatic assembly points of view, featuring two closed loops, a high number of bendings and four ribbon lengths.

The behavior of the flexible ribbon between the connectors was not easily predictable and impossible to simulate with the software available. However, the control of that part was necessary, to avoid stressing the ribbon, curving it below the allowed bending radius or creating undesirable interferences in the working area. For this reason, a few modifications were applied to the task operations after their first run and to the devices and components to improve the ribbon manipulation and assembly.

Fig. 2 shows the final work-cell and the final prototype of the interconnect circuit that resulted from the successful implementation of the automatic assembly process. Indeed, the enabling technologies presented in the paper were implemented for both the design and manufacturing of the different devices and tools, and the planning and execution of the different steps of the assembly process.

5 Conclusions

The implementation of advanced manufacturing and digital technologies is currently considered a key factor for the development of intelligent and interconnected systems, according to the Industry 4.0 paradigm.

In this framework, this paper discussed the exploitation of a set of enabling technologies for the conception and set up of a novel robotized work-cell for the automatic assembly of optical interconnect sub-circuits that constitute an innovative optical backplane. Indeed, optical backplanes appear as a promising solution for the development of high capacity ICT apparatuses that could impact the whole ICT sector.

To this end, a synergic integration of robotics, vision and force sensing, additive manufacturing, digital design and simulation, and off-line programming proved to enable the automatic assembly task.

An improvement in the choice of the robot path planning would derive from the use of a simulation environment able to take into account the behavior of the flexible and free part of the ribbon between the two termination housings.

Moreover, the engineering of the end-effector should consider the possibility to manipulate ribbons shorter than the current minimum length. Indeed, in case of non-simultaneous gripping, the current manipulation tool preliminary prototype cannot manipulate ribbons with free length less than 85 mm. However, in the case of the +1 routing, it would be necessary to use shorter ribbons so that they could be accommodated in the frame. An alternative would be the reduction of the angular offset between the two grippers, then verifying again that they do not collide with the ribbon plane on the assembly tool. A second solution would consider an alternative mounting of the grippers where, for example, one gripper would be mounted horizontally, while its fingers would be mounted in order to project the picking point as required.

Future developments of this work include the extension of the study to the automatic mounting of the termination housings on the connectors. The ribbons could be arranged in the ribbon buffer in a different way, avoiding the need for operator interventions. In a general case the ribbon could be randomly arranged on a plane, and the vision system mounted on the robot end-effector would recognize the termination housing and identify their pose to be sent to the robot controller to enable them to be picked.

Moreover, the online virtual monitoring of the task execution could allow for a remote verification of unpredictable situations and a rapid intervention. Finally, the provision of an interconnection network for the smart integration of the work-cell in the manufacturing plant at different process levels would further pave the way for its successful industrial exploitation.

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