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Abstract:

Nowadays the *Smart Factories* operating within the Industry 4.0 revolution, require more and more reliable, fast and automatic tools for production analysis and improvement. Manufacturing companies, in which the human labour has a crucial role, need instruments able to manage complex production systems in terms of resource utilization, product mix, component allocation and material handling optimization.

In this context, this work presents an original hardware/software architecture, Motion Analysis System (MAS), aimed at the human body digitalization and analysis during the execution of manufacturing/assembly tasks within the common industrial workstation. MAS is based on the integration of the Motion Capture (MOCAP) technology with an *ad hoc* software developed for productive and ergonomic analysis of the operator during his work. MAS hardware integrates a network of depth cameras initially developed for *gaming* (Microsoft Kinect v2™, conceived for markerless MOCAP) and now used for industrial analysis, while an original software infrastructure is programmed to automatically and quantitatively provide productive information (human task analysis in terms of time execution and used space within the workplace, movements of hands and locations visited by the operator) and ergonomic information (full body analysis implementing all the internationally adopted indexes OWAS, REBA, NIOSH and EAWS). This double perspective makes MAS a unique and valuable tool for industrial managers oriented to the workplace analysis and design (in terms of productivity) without neglecting the operator health. This proposed contribution ends with a real industrial application analysing a water pump assembly station: the system setup is discussed and the key results obtained adopting MAS are presented and analysed.

Keywords: Motion Capture, Industry 4.0, Manufacturing, Assembly, Ergonomics.

1 Introduction

The industrial environment is currently experiencing its fourth revolution. The use of ubiquitous sensors connected through communication networks enables the real-time integration of systems, machines, tools, operators, customers and products defining the so called *Smart Factories* (Dujin et al., 2014). These features allow to develop a novel production paradigm, called personalized production. The customers are involved in the product personalization since the design phase to manufacture and assembly unique products which fulfil unique needs (Dou et al., 2014). This paradigm dramatically increases the complexity of manufacturing processes and the variety of assembly operations (Bortolini et al., 2017a). The required production flexibility is typically ensured by skilled and experienced operators which perform the non-repetitive and added-value activities (Bortolini et al., 2017b). Thus, the virtual representation of these tasks (e.g. virtual reality) can be a great help to analyse and improve the manufacturing and assembly processes as well to capitalize the operator knowledge and expertise (Geiselhart et al., 2016).

In this context, Motion Capture (MOCAP) represents a promising solution both to capitalize the worker skill and to prevent possible injuries during the execution of manufacturing or assembly tasks. This solution enables to accurately record the activities of the human body proposing a virtual representation of the skeleton and its movements. Purpose of all the different MOCAP technologies is to sample many times per second the postures held by the monitored actor. The recorded data are then mapped into a 3D model of the human skeleton so that the virtual model performs identical motions compared to the tracked actor.

Considering this current scenario, this paper presents an original Motion Analysis System (MAS) for human body digitalization and analysis for manufacturing and assembly processes. This research develops a hardware system adopting commercial MOCAP devices (conceived for *gaming*) extending their applicability to the industrial sector and integrating them with an original analysis software programmed for the dynamic assessment of the work content. MAS acquires the operator activities during his manufacturing or assembly tasks and it evaluates them from a double perspective: productive and ergonomic viewpoint. The productive viewpoint deals with the time and the space resulting from the analysis of human tasks, movements of focused body parts, occupied locations over time and travelled distances (body, hands, feet, etc). The ergonomic viewpoint is estimated with a full body analysis measuring the human skeleton movements during the operator working activities investigating the evolution of the joint angles and the bone postures.

According to this purpose, the remainder of this paper is organized as in the following. Section 2 analyses the different technologies commercially available for MOCAP, the most relevant contributions to MOCAP usage in the industrial environment and the methods and approaches proposed by the literature to assess the ergonomics of working conditions. Section 3 presents the hardware and software architecture developed for the automatic and quantitative evaluation of the technical and ergonomic performances of an operator during manufacturing or assembly activities. Section 4 describes the MAS application to a case study of a manual assembly process of a gearbox in an industrial assembly station, whereas Section 5 presents and discusses the case study key results and main outcomes. Finally, Section 6 concludes the paper and suggests future research opportunities.

2 Literature review

This Section presents the most relevant contributions proposed by literature which investigate the adoption of MOCAP technologies in the industrial environment (Section 2.1) and the different methods and approaches available to assess the ergonomics of operator working conditions (Section 2.2).

2.1 MOCAP technologies in the industrial environment

The adoption of MOCAP technologies in the industrial environment is a relatively recent field of research. Until few years ago, these solutions were extremely costly, required meticulous and time expensive set-up procedures and did not offer completely reliable results from the precision perspective (Oyekan et al., 2017).

Du and Duffy (2007) proposed the first contribution to digitalise the human body of an operator during assembly activities through a MOCAP technology. Three different technologies have been developed so far to ease the tracking of human movements.

Marker-based optical MOCAP exploits active or passive markers properly displaced in specific part of human body. A bunch of cameras detects the position of each marker in its own two-dimensional (2D) field of view, whereas the relative position and orientation of cameras enable to triangulate the location of markers in the 3D space of action (Tian and Duffy, 2011). The markers can be either active or passive. Active markers are LEDs which typically emits their own light one at a time at high frequency. On the contrary, passive markers are small plastic spheres coated with a retroreflective material to reflect the light that is generated near to the camera lens by an infrared emitter (Ceseracciu et al., 2014).

Inertial MOCAP technology is based on miniaturized inertial sensors which are properly displaced on the body parts to monitor. Each inertial measurement unit (IMU) is equipped with a gyroscope, a magnetometer and an accelerometer to record their relative measures on each of the three geometrical axis (Bourke et al., 2008). However, compared to optical MOCAP, the inertial approach is affected by a lower accuracy of the absolute location of the limbs due to positional drift which can compound over recording time. Thus, this technology presents several limitations and drawbacks for its application in manufacturing or assembly shop floors, and, in general, in the industrial environment.

Marker-less optical MOCAP represents a recent advance in the technology to avoid the awkward suits which have to be worn by the operator in case of marker-based optical or inertial MOCAP. Indeed, both these technologies typically require active and passive markers as well as IMUs to be mounted on cumbersome suits. On the contrary, marker-less optical MOCAP free the operator to perform his activities in his regular outfit (Geiselhart et al., 2016). Nguyen et al. (2013) first adopt this solution to monitor the postures and movements of a human operator during manual manufacturing processes with promising results both in term of measurement accuracy and system set-up easiness.

The adoption of MOCAP technologies in the industrial environment achieved a relevant importance with the Factory of the Future (FoF) concept (Jardim-Goncalves et al., 2017, May et al., 2016). In these factories the operators perform complex and non-repetitive tasks to comply to the personalized production paradigm (Faccio et al., 2015). The operator expertise is one of the most valuable competitive advantages owned by the FoFs (Fantini et al., 2014). MOCAP technologies are of major help for the tracking of the unique manual assembly or manufacturing processes to later capitalize the operator knowledge (Alnahhal and Noche, 2015, Romero and Vernadat, 2016). Furthermore, the recent socio-economic trends suggest or even forces the FoFs to evaluate and improve the working conditions of their operator and the related ergonomics (Honglun, 2007). Finally, production and ergonomic performances are strongly interrelated. The actions designed and implemented to improve one performance category have an impact on the other, not necessarily positive (Xu et al., 2012, Accorsi et al., 2017). Thus, any approach or solution aimed at the simultaneous optimization of the manufacturing and assembly processes from both the production and ergonomic perspectives is strongly encouraged (Gragg et al., 2013).

From the production perspective, marker-less optical MOCAP is adopted by Agethen et al. (2016a and 2016b) to analyse the discrepancies between the planned and the real manual production process, which typically remain unknown without appropriate monitoring tools. The authors exploit this tracking system to reconstruct the operator motion within an assembly line. Similarly, Geiselhart et al. (2016) adopted a marker-less optical MOCAP system to measure the production performances in real working conditions compared to the one forecasted by simulation models and methods. From the ergonomic perspective, the pioneering contribution of Jayaram et al. (2006) exploits inertial MOCAP to automatically assess the ergonomics of different postures assumed by the operators during their working activities. From the ergonomic analysis perspective, two contributions aim at improving the ergonomic evaluation. Vignais et al. (2013) assess the risk of possible disorders for each body part adopting an inertial MOCAP technology along with a specific ergonomic index. Kim and Nussbaum (2013) further detail the ergonomic evaluation assessing the evolution over time of the angle of most of the skeleton relevant joints. Furthermore, some authors recently exploited the emerging marker-less optical MOCAP technology for the ergonomic assessment in real industrial environment. Both Geiselhart et al. (2016) and Plantard et al. (2016) integrate multiple depth cameras to increase the accuracy and the covered area of the monitored human motions with promising results.

2.2 Methods and approaches for the ergonomic assessment of working conditions

During the last decades, several methods and approaches are proposed by literature contributions to assess the ergonomics of operator working conditions (Li and Buckle, 2017). In the last years, these indices are adopted by the authors which developed MOCAP systems to quantitatively and univocally assess the ergonomic performance of the operators during manual assembly or manufacturing activities (Shikdar et al., 2002). The ergonomic indices are classified in the following with respect to the targeted manual handling activity.

Lifting and carrying tasks are traditionally assessed through the NIOSH equation (Waters et al., 1993). This method determines the recommended load weight limit for human lifting operations. Pushing and pulling activities along with force limit considerations are assessed by Snook and Ciriello (1991). The manual handling of low loads at high frequency is carefully analysed by Occhipinti with the proposed OCRA index (1998). Similarly to OCRA, the Strain Index (Moore and Garg, 1995) estimates the risk of distal upper extremity disorders analysing different features of a performed task. Furthermore, operator posture and movements are carefully assessed by three indices. Indeed, both OWAS, RULA and REBA analyse the working posture of an operator evaluating the position of the different body parts and the angle of several skeleton joints. However, the OWAS index qualitatively estimate the body posture (Karhu et al., 1977). RULA carefully assess the upper limbs but it poorly estimates the posture of lower limbs, the legs in particular (McAtamney and Corlett, 1993). REBA index is distinguished by the advantages of RULA one along with a proper and thorough evaluation of lower limbs posture (Hignett and McAtamney, 2000). Finally, Schaub et al. (2013) aim to integrate the different features of most of the aforepresented ergonomic indices in a unique indicator for manual assembly or manufacturing activities. The proposed EAWS index consists of four sections for the evaluation of, respectively, working postures and movements with low additional physical efforts (similarly to REBA index), action forces of the whole body or hand-finger system (Snook and Ciriello, 1991), manual materials handling (NIOSH index) and repetitive loads of the upper limbs (OCRA index). The following Table 1 summarizes the features of the presented indices for the ergonomic assessment of manual assembly or manufacturing activities.

Feature	*NIOSH*	*Snook & Ciriello*	*OCRA*	*Strain Index*	*OWAS*	*RULA*	*REBA*	*EAWS*
Posture			x	x	x	x	x	x
Upper limbs			x	x		x	x	x
Lower limbs					x	x	x	x
Spine	x				x	x	x	x
Quantitative	x	x	x	x		x	x	x
Load/Force	x	x		x		x	x	x
Frequency	x	x	x	x				x
Duration		x	x	x				x
Recovery			x					x

Table 1. Features of the ergonomic indices for the manual assembly or manufacturing activities.

Considering the revised literature and as far as these Author knowledge, this paper presents one of the first research contribution of MOCAP technologies for industrial applications which proposes the simultaneous assessment of the production and ergonomic performances of a human operator during assembly or manufacturing activities. Despite the previous contributions, the developed MAS, based on marker-less optical MOCAP technology, avoids any interference with the worker activity, which is typical of the MOCAP solutions which adopt cumbersome suits. Furthermore, the selected marker-less cameras ensure a remarkable measurement accuracy of both the operator posture themselves and his movements in relation to the machines and components displaced in the shop floor. Finally, the proposed MAS automatically and quantitatively assesses a bunch of ergonomic indices to estimate the operator musculoskeletal performance and it measures a set of productive key performance indicators (KPIs). The latest research trends have been investigated to identify the most relevant productive KPIs to be assessed through the developed MAS. Agethen et al. (2016b) remark the importance of accurately evaluate the paths travelled by the operators within an assembly or manufacturing station, whereas Bin Che Anu et al. (2014) suggest to analyse in detail the production processes to measure the added value portion of the working time. Concerning manual picking activities, a proper analysis has necessarily to monitor the instant, frequency and duration of retrieval tasks from each possible storage location of the shop floor (Thomas and Meller, 2015).

3 Motion Analysis System description

MAS is an original hardware/software architecture conceived for the analysis of human manufacturing and assembly systems. It is developed for adapting itself to the typical workplace configurations and its aim is to analyse the human work providing the production management with a very detailed report from both the productive (time and space) and ergonomic point of view (see Figure 1). The aim is achieved by a human markerless MOCAP hardware system developed for the digitalization of the operator body during his work and an *ad hoc* software programmed to perform dynamic analysis.

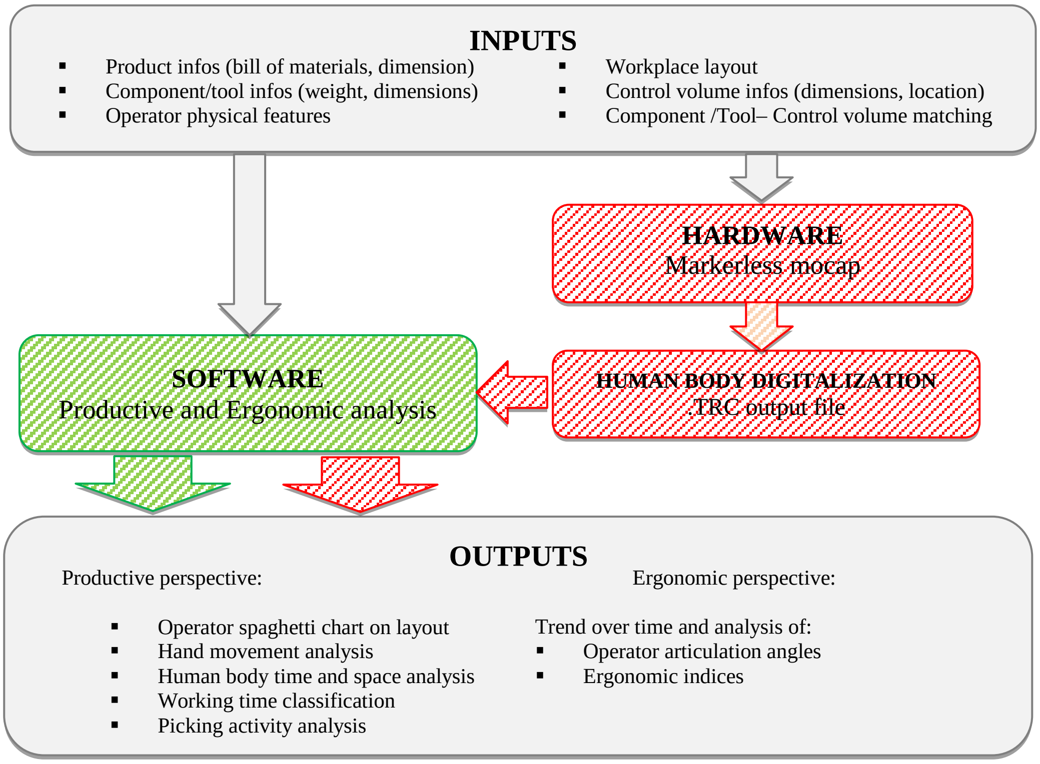


Figure 1. MAS conceptual framework.

3.1 Hardware architecture

The hardware structure of MAS is constituted by a Wi-Fi network with up to four depth cameras connected each one via USB port to dedicated PCs. The adopted PCs have to be equipped with high-performance graphic cards which allow to process the huge data flow of images acquired from each camera during MOCAP operations. Between the PCs, one acts as *master* while the others are the *slaves*. This system configuration, depicted in Figure 2, allows to synchronize the four image flows thanks to the Wi-Fi communication between the *master* and *slave* PCs.

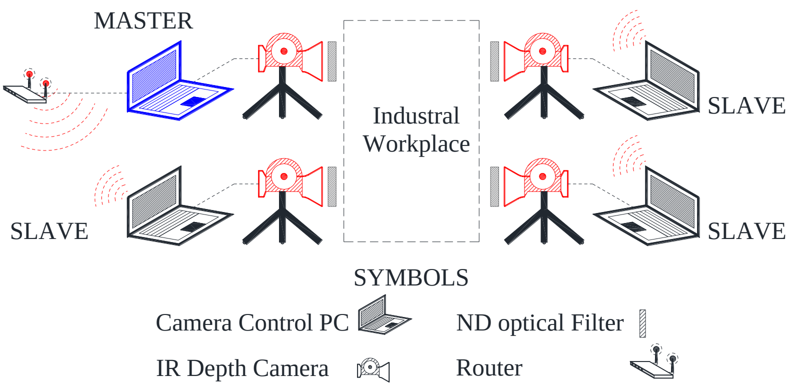


Figure 2. MAS hardware architecture

The used depth cameras are the Microsoft Kinect v.2™ (https://developer.microsoft.com/en-us/windows/kinect/hardware) derived from the gaming sector but thanks to the Microsoft™ Software Development Kit (SDK) they are now configured and used for human tracking in industrial applications. The cameras have two parallel sensors for a best depth evaluation: a color RGB sensor and a IR depth sensor. Their features and performance are summarized in the following data and in Figure 3:

- ✓ RGB sensor, resolution 1920x1080 @ 30fps;
- ✓ IR sensor, resolution 512x424 @ 30fps
- ✓ FOV (field of view), horizontal 70°, vertical 60°;
- ✓ Min/Max depth distance, ~1.4m / ~5m;
- ✓ Skeleton detectable joints, 26;
- ✓ Contemporarily acquirable operators: 2.

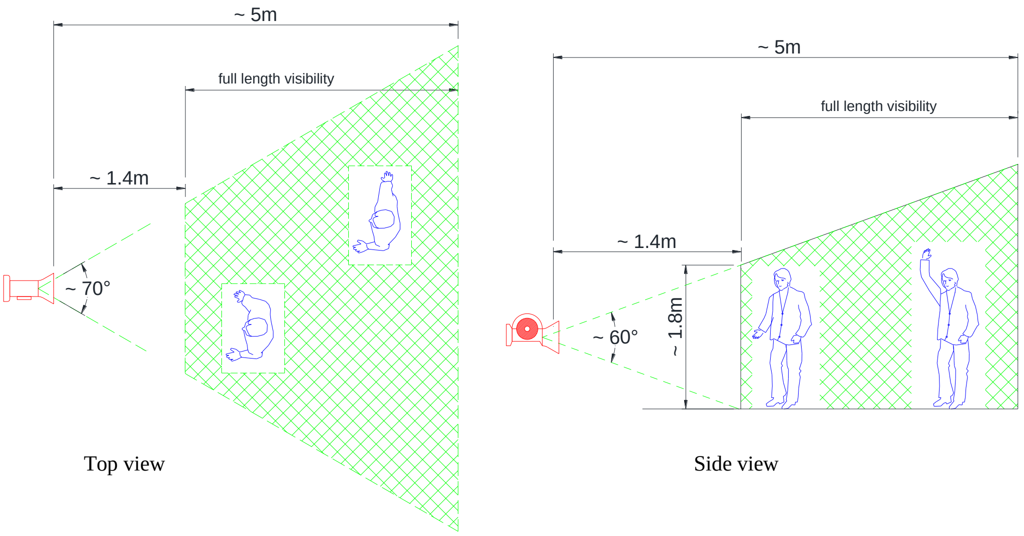


Figure 3. Depth camera field of view.

The depicted spatial field of view of the cameras is the result of an experimental campaign aimed at the investigation of the operating limits of the adopted hardware. A real industrial workplace is settled within the Laboratory of the Department DIN of the University of Bologna for this purpose.

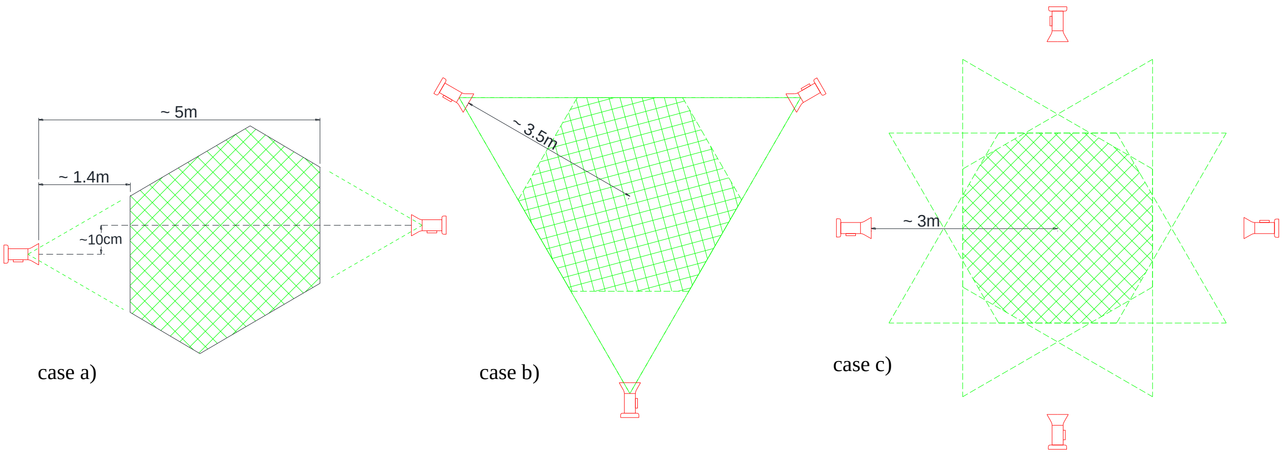


Figure 4. Ideal camera configurations for MAS with two (case a), three (case b) and four (case c) cameras.

As result of the *on field* analysis, the position of the cameras must be carefully chosen to maximise the acquisition precision and the industrial area covered. According to the camera performance three *ideal configurations* can be used and the Figure 4 depicts them. These configurations are defined *ideal* because in these conditions the best measurement precision for a skeleton acquisition can be achieved: the *positional error* between the digital and the real skeleton position is measured in about ~3-4cm.
Despite of these ideal configurations, the system can excellently work adapting the position and the number of the cameras to the specific case study, according to the real layout and constraints of the manufacturing/assembly workplace. Several *real* configurations are experimented with two, three and four cameras and large obstacles (shelves, tables, tool trolleys etc.) within the camera field of view. The next Figure 5 shows the trial workplaces distinguished by low and high obstruction levels (for sake of brevity, all the intermediate configurations investigated but not presented, are omitted).

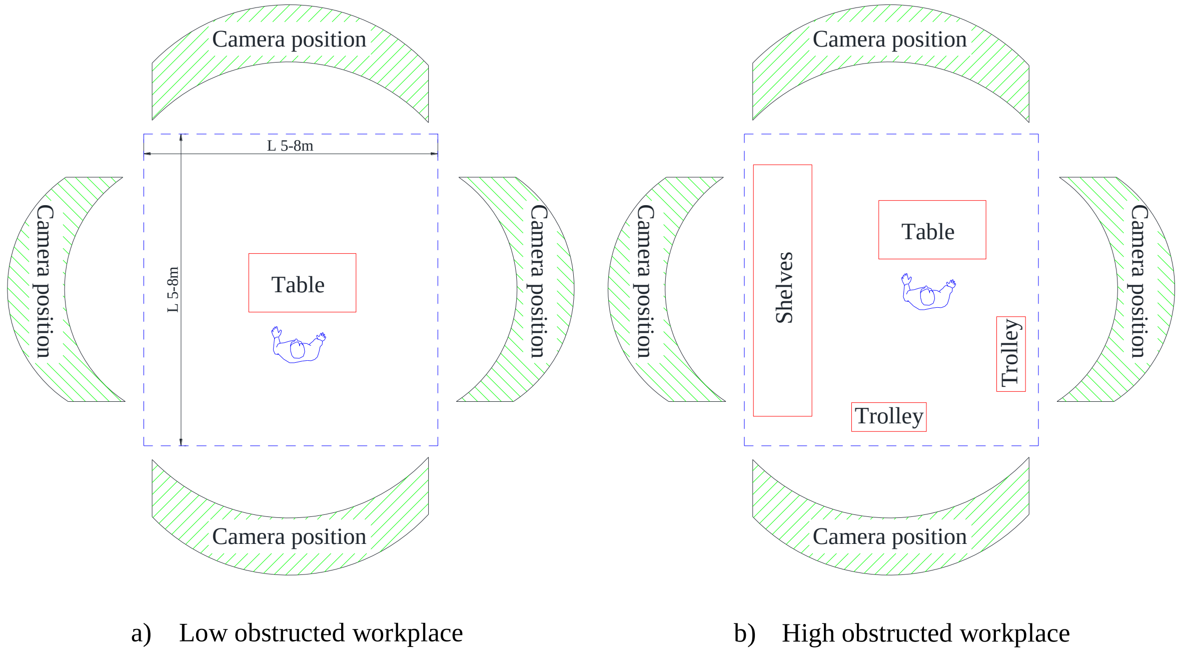


Figure 5. Trial workstation for experimental campaign.

Seven people, both female and male, with different physical morphologies participated to the experimental campaign. The people heights vary from 157 to 193 cm accordingly to the following values: 157, 168, 175, 178, 182, 186 and 193 cm. Each participant performs 9 times a specific set of predetermined identical activities for a duration of 8.4 min. To evaluate the 3D spatial precision of MAS, each task requires the operator to touch with his hand or foot several predetermined markers on the workplace (e.g. tools, markers on tables, on shelves or on the floor). The experimental campaign aims to evaluate for each monitored operation the error between the real and the tracked 3D position of the considered joint. The average tracking error and its standard deviation are calculated accordingly and they result in a remarkable tracking precision distinguished by an average accuracy of 5.2 cm with a standard deviation of 0.8 cm.

Another important detail necessary for the application of such depth cameras to a real industrial environment, is the light level management. Indeed, depth cameras are very sensitive to high light level and they cannot properly operate if the environment is highly illuminated. To overcome this limit, the authors provided each camera with a tailored Neutral Density (ND) filter mounted on the RGB and IR sensors. This ND filter is necessary to enlarge the light contrast range of the Kinect v.2™ device ad it must be chosen from ND=0.3 to ND=3.8 in relation to the intensity of the bright surfaces (windows, lights, reflective metal surfaces, etc.) within the area to analyse. Without the ND filter, the system performance dramatically decreases.

3.2 Software architecture

The software providing the dynamic analysis of the working operator is developed in Matlab™ environment and it is conceived to elaborate the human body digitalization coming from the depth camera network previously discussed. Up to two operators can be contemporarily monitored within the covered area presented in Figure 4. The digitalization of their bodies consists in the process of recording the movement of their skeletons. The resulting output file stores the positions of all body joints over time. The chosen standard for the proposed architecture is the .TRC file format (introduced by Motion Analysis inc. https://research.cs.wisc.edu/graphics/Courses/cs-838-1999/Jeff/TRC.html) which supplies the position of all the joints of the analysed human body. Such joints are named with the MOCAP standardized terminology widely adopted in the cinematography industry and by MOCAP commercial software (see Figure 6).

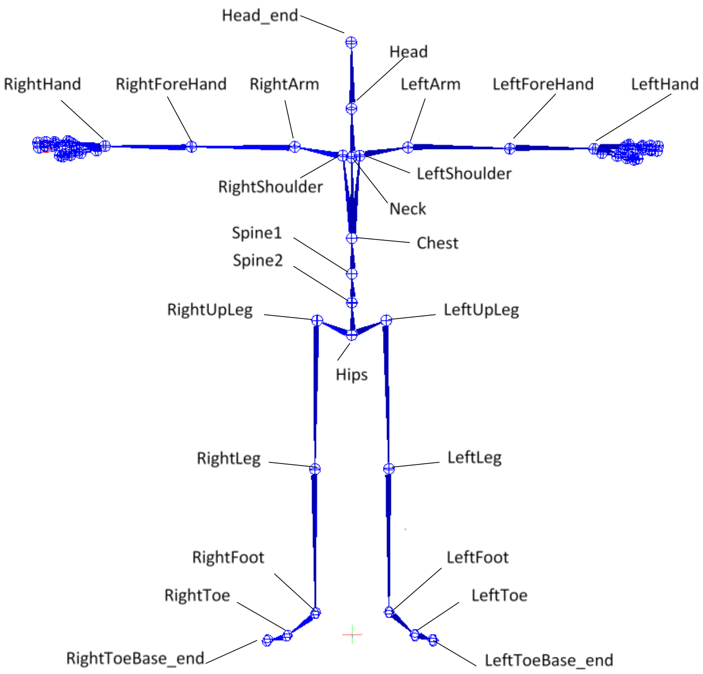


Figure 6. Skeleton joints of the acquired human body

The set of joints together with their position vector are the necessary information to analyse the manufacturing/assembly process together with additional information regarding the area in which the operator works and the product he manufactures or assembles.

The required input information is of different type:

- Physical features of the operator, height in particular: necessary for the MAS to acquire and evaluate the skeleton dimensions (length of each limb);
- 3D workplace layout including position and geometrical dimensions of machines, racks, shelves, workbenches, etc.: the 3D environment in which the operator is immersed and works has to be detailed in terms of object geometrical dimensions and zones;
- Information of the product to be assembled or manufactured: the product components, dimension and weight (in synthesis the product BOM, e.g. bill of materials);
- Information of the tools necessary for the manual operations: position of tools, their dimension and weight;
- Relation between components and tools used for the final product manufacturing.

The aforementioned information can be easily obtained by the analyst extracting them from the company Manufacturing Execution System and provided to the MAS as .CSV data in a massive way.

For each MOCAP activity all the previous data must be collected at least once. However, it is not necessary to provide them for every replication of the same scene because the information is invariant from the replication.

The developed software has a double perspective providing information on both the productive and ergonomic and point of view. Indeed, MAS is focused on the whole manufacturing analysis integrating the working condition improvement (ergonomic viewpoint) with the production enhancement (productive viewpoint).

These viewpoints are not related to the production mix. The MAS is not affected or influenced by the product type assembled by the operator. Indeed, the proposed architecture is able to track the operator motion whatever the assembled or manufactured products are. The performed experimental campaign validates the adoption of MAS for production systems distinguished by small to medium size products of whatsoever shape, volume and weight. As previously stated in the Section 3.1, the MAS is able to contemporarily track 2 operators which perform their activities in the same shared workstation even in case of interaction or collaboration.

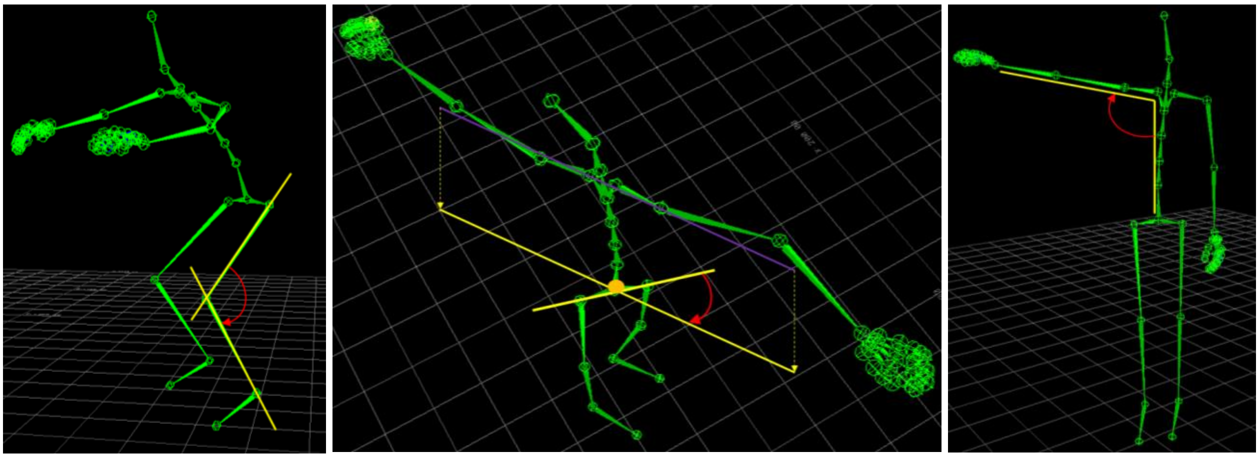
Aim of the MAS is to evaluate the performance of manual operations during an assessment trial quantifying the productivity and the ergonomics of a workstation. The productive viewpoint is assessed through a dynamic analysis of the operator movements in relation to the workplace layout in which the tasks are executed (manufacturing activities, task execution time, component locations, workspace usage, racks or workbenches utilization, hands position, etc.). The ergonomic viewpoint consists in the evaluation of several ergonomic indexes internationally defined and approved (e.g. OWAS, REBA, NIOSH and EAWS).

The aforementioned results are obtained evaluating the .TRC file containing the position vector of all the operator joints over time. The structure of this file format is presented in Table 2. The position vectors (X, Y, Z) of each joint is listed and stored frame by frame providing a dynamic representation of all the movements executed by the operator.

Frame#	**Time**	**Reference**			**Joint1: Hips**			**Joint2: RightUpLeg**			**Joint3:….**
		X1	Y1	Z1	X2	Y2	Z2	X3	Y3	Z3	…
1	0	0	0	0	0	1000.71	28.2	-133.42	985.79	-226.8	…
2	0.033	0	0	0	23.01	1001.14	-16.14	-167.27	985.20	-177.4	…
3	0.067	0	0	0	22.81	1000.95	-16.00	-173.33	984.54	-179.4	…
4	0.1	0	0	0	22.44	1001.10	-15.87	-174.61	983.99	-184.76	…
5	0.133	0	0	0	22.13	1005.53	-15.91	-180.52	988.521	-194.92	…
6	0.167	…	…	…	…	…	…	…	…	…	…

Table 2. TRC file structure example.

All this information enables to determine the angle of every human body articulation for each monitored frame, thus all displacements and postures of the operator are considered and quantitatively measured.



Knee angle Trunk rotation Shoulder lateral elevation

Figure 7. Examples of angles calculated by MAS.

All the angles are automatically determined in the 3D space (see Figure 7) and, along with the joint position vectors, they enable to evaluate the productive and ergonomic KPIs illustrated in detail in the next paragraphs.

3.2.1 Productive viewpoint

The information about the operator working performance provided by the MAS is:

- *Time and space analysis* of the workplace areas (task execution times, travelled paths by the operator, time spent in adjacency of the workstation objects (machines, racks, shelves, workbenches, etc.));

- *Hand displacement* over time and velocity trend;
- *Cumulative vertical movements* for lifting and lowering;
- *Control volume analysis*[1] for the distinction between added-value and no added-value activities;

3.2.2 Ergonomic viewpoint

The information about the operator ergonomic performance provided by the MAS deals with the evaluation over time of several indexes measuring the body postures and movements:

- *Articulation angle analysis* applying the ISO 11226 standard to classify as acceptable or not the worker postures;
- *OWAS, Ovako Working posture Assessment* (Karhu et al., 1977), for entire body analysis;
- *REBA, Rapid Entire Body Assessment* (Hignett and McAtamney, 2000), for entire body analysis;
- NIOSH, *National Institute for Occupational Safety and Health* index (Waters et al., 1993), for weight lifting activities;
- EAWS *European Assembly Worksheet* (Schaub et al., 2013), for entire body analysis and specific of the automotive sector.

4 Real case application setup

To apply and to validate the developed MAS architecture, the case study of a real assembly station designed to assembly industrial water pumps is presented. This real application follows the tests and validations performed in the Mechanical Laboratory of Department DIN of the University of Bologna previously mentioned in Section 3.1. This Section presents a real application to highlight the feasibility of the proposed architecture showing the main results and findings.

The final aim of MAS it to automatically and quantitatively assess the operator productive and ergonomic performance. In particular, the most relevant KPIs concern the operator walking path within the station layout, his hand distribution on workbench, the added value portion of the cycle time, the body posture assessment and the REBA ergonomic index evaluation.

The analysed product is assembled over a moving workbench and an operator has to manage several components placed in racks and pallets around him. The pump assembly must be executed within the *cycle time* of 5.5 min/pcs (the cycle time coincides with the MOCAP time horizon). The product (see Figure 8) and

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[1] In the MAS environment, the analyst can define 3D control volumes within the workplace (defining their dimensions and 3D position) to achieve an in-depth statistic about the locations most visited by the worker hands over time. Creating and placing control volumes on the workbenches, in the picking positions, within specific shelfs or racks or in whatsoever location, allows to distinguish between the operator picking or travelling time (no added-value activity) and the manufacturing time (added-value activity) in relation to the number of visits to control volumes and their average duration for both the operator hands.

its components are well known as well as the detailed bill of materials, the component dimensions and weights.

For the considered case study, one male operator 178cm high is involved in the experiments capturing his motions for the duration of one cycle time (5.5 min) without any interruptions while he is performing the required 18 assembly tasks on the only product considered, e.g. the commercial water pump pictured in Figure 8.

Figure 8. Water pump assembly (left) and main components (right).

The analysed workplace, depicted in Figure 9, is organized with an assembly station connected with the other production phases through conveyor rollers. The area is provided with front and rear racks to respectively store the small- and medium-sized product components, an europallet for large components and a mobile trolley containing the tools and bits required by the operator. All their dimensions and 3D positions are known and acquired. The gross area is approximatively 20sqm and a quasi-rectangle displacement of the depth camera is adopted to capture the movements of the operator which can dress any type of quite slim clothes (to reduce the noise in the joint position acquisition) without restriction of colours.

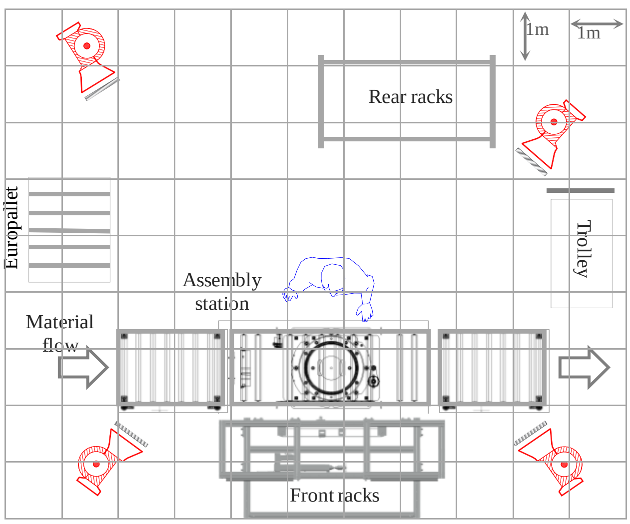
From the privacy perspective, the utilisation of MAS architecture within an industrial environment is compliant with the recent EU General Data Protection Regulation (GDPR) (2016). In particular, three major GDPR principles have been fully considered and implemented to ensure an adequate protection of the personal data of the involved operators. First, the “privacy by design principle” is implemented during the MAS development to ensure the personal data protection at any stage of the assessment activity. Second, the “right to be forgotten” principle is ensured through the possibility for any worker to request at any time and immediately obtain the removal and deletion of all the data dealing with his person. Third, the “principle of transparency” of the data usage is guaranteed through a formal agreement between the involved operator and the employer. The aforementioned agreement should ensure the operator privacy and personal data protection through regulating the relationship between the parties in terms of:

- *Purpose of MAS adoption*. The employer has to inform the employee for which purpose the collected data are used, to evaluate which aspect of the performed tasks.

- *Privacy protection*. The collected data are acquired completely anonymously without any possibility to match the information obtained with a specific employee.
- *Data protection*. The collected data are stored only for the time and to the extent necessary to the workstation analysis. The aforementioned data can be processed and analysed only by the authorized analysts which have be clearly designated in this agreement indicating their name, role and division within the company.
- *Duration of tracking period*. The employer has to explicitly inform the employee every single time in which the MAS is used for tracking purpose. In any case, the frequency and duration of the recording phase has necessarily to represent a limited portion of the worker shift duration with no intent or purpose of continuous monitoring.
- *Recording technology specifications*. The employer has to indicate the model of the depth camera adopted for MOCAP purpose along with the camera number and location within the workstation layout. Further specifications to be provided are the camera field of view, the tracking distance and the areas of the layout monitored by the cameras.

Furthermore, a specific demonstrative session has to be organised by the employer which adopts the MAS architecture to actively involve the operator in the assessment process. During this session, the architecture has to be tested by the workers providing them all the specifications and details about its functioning principles. The employer has to clearly list all the data which the MAS is able to obtain, how they are processed and for which purpose they are used. The session ends with the collection of the worker feedbacks and the possibility for them to make whatsoever question and obtain detailed answers.

Finally, MAS is conceived to be adopted to analyse an industrial workstation to assess if there are improvable configurations of work both from the productivity and from the ergonomics point of view. From the privacy perspective, the MAS architecture does not differ from the traditional processes adopted in the industrial workshop to assess the operator productive and ergonomic performances (e.g. Time and Methods or Ergo-analyses) which consists in recording a video of worker usual tasks for a limited time period (e.g. a cycle time). Nowadays this is a common practice considering the increasing penetration of ICT devices in the industrial production management.



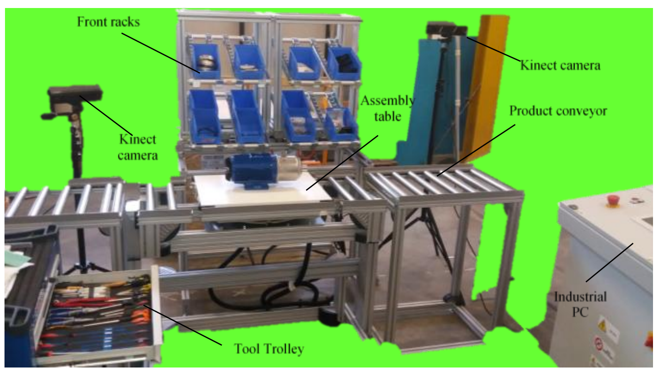


Figure 9. Assembly station: scheme (left) and front-view picture (right) masked for confidentiality reasons.

The four cameras are connected to one Intel i7-processor PC (master) and three Intel i3-processor PC (slaves) with adequate GPU performance necessary to guarantee an acquisition frame rate equal or higher than 30fps. The used operating system is Windows 10™. The average storing capacity required is 30Mbyte per second of acquisition and camera. Thus, the four camera motion analysis and the *cycle time* of 5.5 min/pcs require a total hard disk space of 39.6 Gbyte.

5 Results and discussion

In this context, MAS is used to analyse the work execution and the consequent output results both from the productivity and from the ergonomics perspectives. Considering the several and different KPIs which the MAS is able to evaluate, the following table of contents presents a rationale and offers an overview of this Section 5 articulation:

- Productive perspective:
  - analysis of the operator and upper limbs movements,
  - operator walking path within the station layout,
  - hands distribution on workbench,
  - cycle time partition between the different working activities;
- Ergonomic perspective:
  - articulation angle analysis and posture assessment through ISO 11226,
  - dynamic evolution of REBA ergonomic index,
  - average REBA score for each body part.

From the productive perspective, MAS automatically and quantitatively evaluates several KPIs. For sake of brevity, the most significant results are presented in this Section.

The next Table 3 proposes the movement analysis of the operator body and both his hands. During the monitored cycle time, the operator walks for a total distance of 34.7 m at an average speed of 6.32 m/min. He experiences the alarming value of 6.0 m as the cumulative vertical movements over the monitored period to lift components from storage locations at ground level. Concerning the upper limbs, the operator performs the assembly tasks with a balanced proportion between the right and left hand usage, e.g. right vs left hand travelled distances 83.4 m vs 81.2 m.

Body part	Traveled distance [m]	Vertical drop [m]	Average speed [m/min]
Right Hand	83.4	34.9	13.6

Left Hand	81.2	33.7	13.3
Operator	34.7	6.0	6.32

Table 3. Analysis of the operator and upper limbs movements.

The movements of the operator and his hands within the assembly station are further in-depth analysed. Figure 10 presents the spaghetti chart of the operator walking path within the station layout detailing the locations visited by the operator during the 34.7 meters listed in Table 3. The irregular pattern is determined by the different picking activities which the operator has to perform between the industrial equipment of the workstation (front and rear racks, europallet and trolley).

The hands distribution on the workbench is presented by Figure 11 (left and right hands separately). The left hand activity is quite confined to the left side of the workbench whereas the right hand performs assembly operations in the central/right portion. Furthermore, the left hand movements are concentrated in a narrow area of the workbench (e.g. 34.2% of the cycle time spent in a 100 cm^2 area, with a peak of 14.9% spent in 25 cm^2). On the contrary, the right hand movements span across the entire workbench. Compared to the left hand, the right one spends a similar amount of the cycle time (37.9%) in an area of double size (200 cm^2).

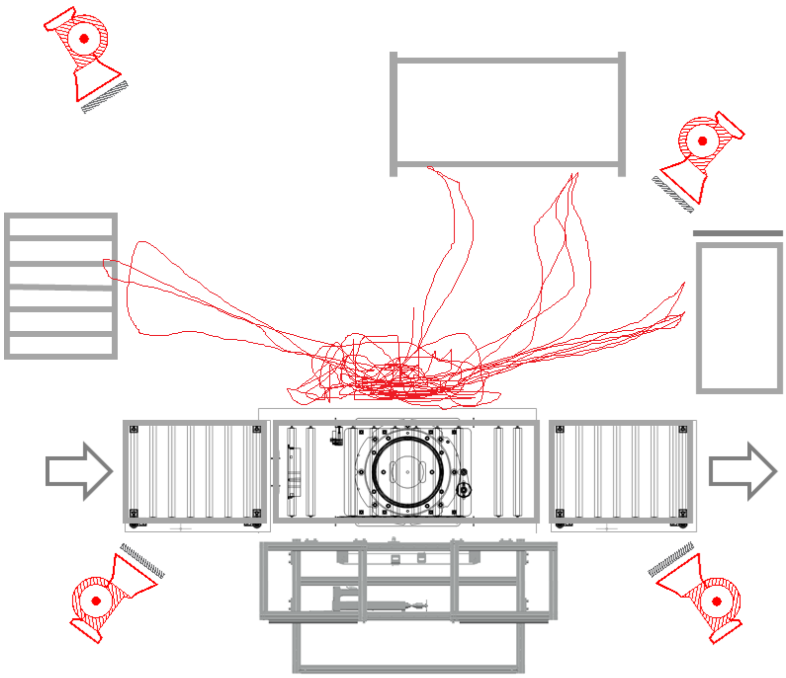


Figure 10. Operator walking path within the station layout.

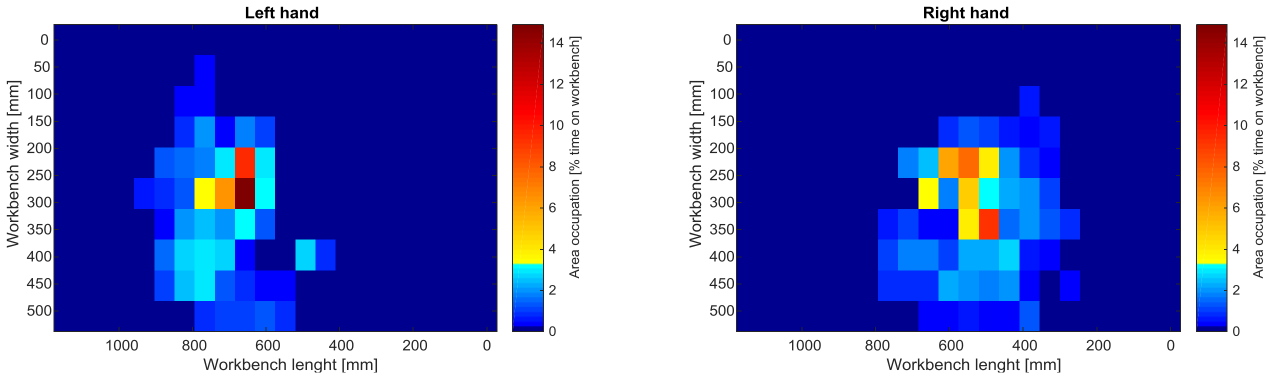


Figure 11. Hands distribution on workbench.

Concerning the different activities performed by the operator during the cycle time, MAS evaluates for each control volume the number of visits and their duration for both the operator hands. This analysis is adopted to assess and to distinguish between the time spent by the operator to execute added-value activities (assembly tasks) and picking/travelling activities. As presented in Figure 12, most of the cycle time (61%) is spent for value added activities (e.g. assembly), whereas a non-negligible portion of it (18%) is wasted to walk inside the station area. Regarding the picking activity (21% of the cycle time), front and rear racks are similarly exploited for component storage purpose (10% and 8% of cycle time, respectively), thus a different disposition of components on storage locations should be addressed in future improvements of the station layout fostering the front locations instead of the rear or lateral ones.

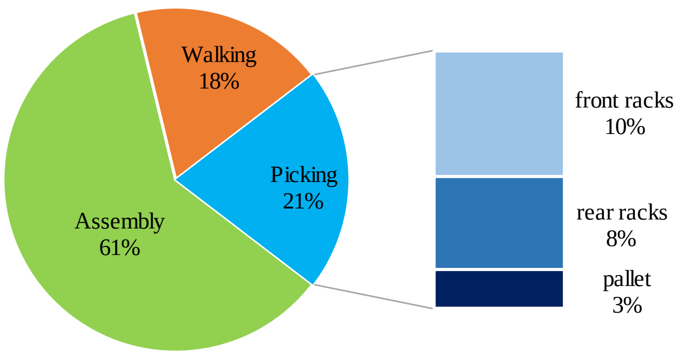


Figure 12. Cycle time partition between the different working activities.

From the ergonomic perspective, MAS proposes a set of quantitative indicators to monitor the operator health during the assembly process discussed in the case study. Several full body ergonomic indexes can be evaluated. For sake of brevity, in this Section the REBA index is the only one presented (see Figure 13) during the *cycle time* of 5.5min/pcs (330 seconds/pcs). The global target of the REBA index suggests that, in this case study, the operator spends most of the cycle time holding postures with null or low risk for his health. However, this index highlights some criticalities at ~110sec and ~290sec in which the operator health is seriously threatened by to medium/high risky postures.

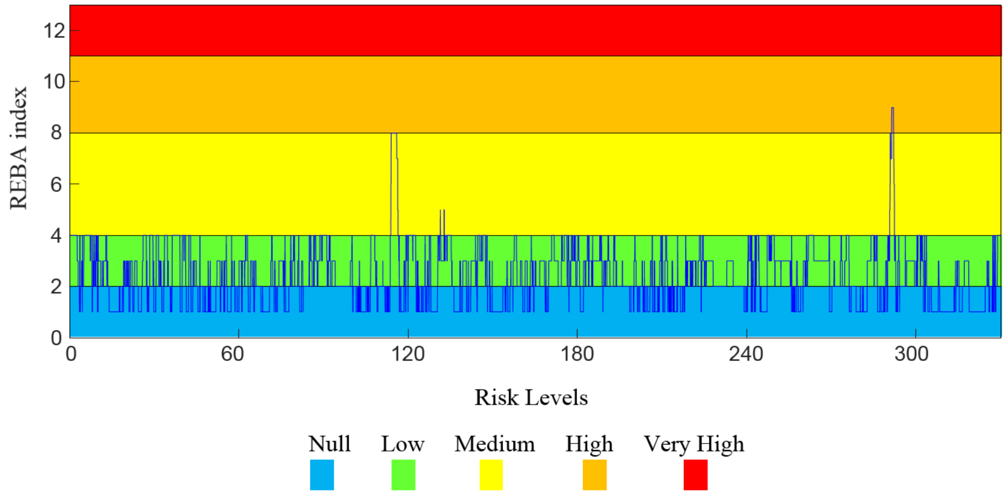


Figure 13. Dynamic evolution of REBA ergonomic index over the cycle time and classification of the risk level for the operator health.

Thus, a further extensive evaluation is required. Figure 14 presents an in-depth analysis of the articulation angle according to the ISO 11226. In particular, the trunk frontal bending together with its rotation are here measured and assessed. The critical tasks overcoming the admissible angles can be highlighted and the related postures are extracted from the 3D skeleton capture.

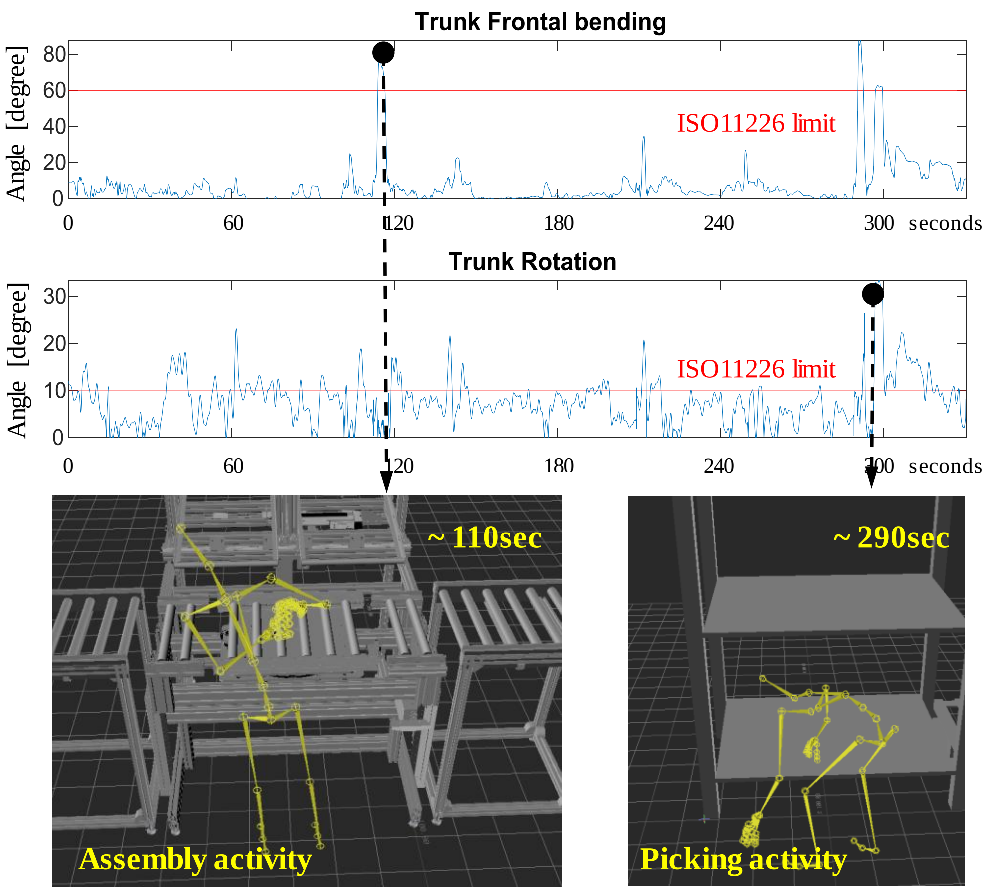


Figure 14. Example of MAS posture assessment applying the articulation angle analysis of ISO 11226.

This analysis allows the production managers to understand what/where/when the manufacturing process should be modified and corrected to achieve a great advantage for the operator health.

Finally, Figure 15 proposes the *average score* of the REBA index split for each limb: left and right upper and lower limbs are independently assessed to analyse the differences between the two body sides. No differences are experienced between the left and right limbs from the ergonomic perspective, expect for the upper arms: the movements performed by the right one are riskier than the activities carried out by the left one. In conclusion, these results suggest that both the neck and the legs do not represent a risk for the operator health, whereas the other body parts are affected by a low risk level (maximum score of 2.5 for left lower arm).

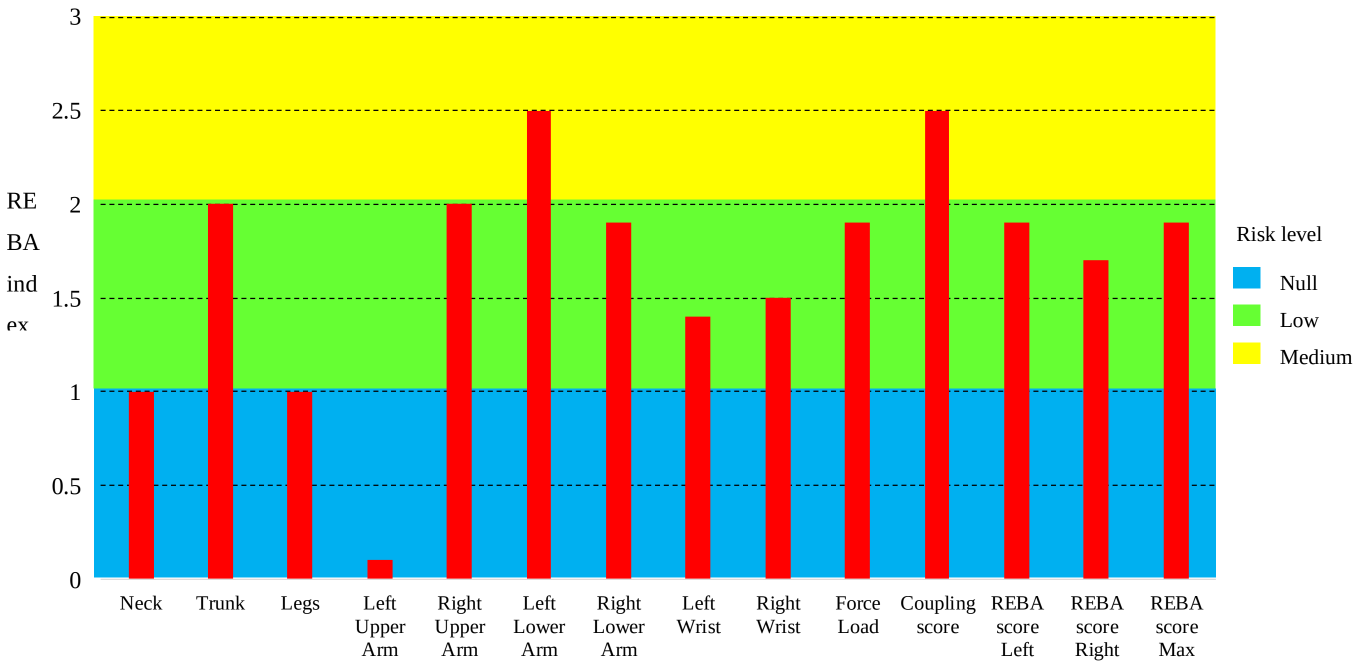


Figure 15. Average score of the REBA ergonomic index for each body part.

6 Conclusions

This paper proposes an innovative hardware/software architecture, called by the Authors Motion Analysis System (MAS), developed for an in-depth evaluation of the human labour content within the manufacturing/assembly workstations.

The MAS exploits commercial Motion Capture (MOCAP) devices (conceived for *gaming*) extending their applicability to the industrial sector and integrating them with an original analysis software programmed for the dynamic assessment of the human labour within an industrial workplace. MAS acquires the 3D representation of the operator during his manufacturing or assembly tasks by means of depth cameras (Microsoft Kinect v2™) using a markerless technology for the human body digitalization. The digital 3D skeleton of the operator is acquired at 30fps storing all the dynamic information of the human movements. This information is exploited by the software section of MAS in which the manufacturing process is assessed from a double perspective, namely productive and ergonomic viewpoints. The productive viewpoint deals with the task execution time and the workspace utilization (travelled distances of the operator and his hands, spaghetti chart, etc.), moreover MAS can distinguish between time and space spent for added-value or non added-value activities thanks to the proposed control volume analysis. The ergonomic viewpoint concerns a full body assessment measuring the human skeleton movements during the activity execution and implementing the evaluation of several international ergonomic indexes (OWAS, REBA, NIOSH, EAWS).

The applicability and usefulness of MAS is discussed in the case study application of a real assembly workstation. A system configuration with four depth cameras is adopted and a single operator is analysed providing both productive and the ergonomic information about the assembly process. The case study results suggest how MAS is a valuable hardware/software architecture to assess a manual manufacturing/assembly workstation highlighting the productive and ergonomic aspects of possible improvements (workstation layout, location of tools or components, musculoskeletal workload etc.).

Concerning further research activities, this paper represents the starting point of a wider project aimed at the manufacturing workplace optimization. The meaningful information provided by MAS concerning different aspects of manual activities has to be integrated with a manufacturing optimization tool able to rearrange the location of equipment and components within the workstation to improve both the productive and the ergonomic performances of the operator. In this context, the MAS is going to be exploited to automatically and quantitatively assess the operator tasks within the industrial workplace before and after the implemented optimization to measure the achieved improvements.

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