Anticipatory models of human movements and dynamics: the roadmap of the AnDy project

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Abstract

Future robots will need more and more anticipation capabilities, to properly react to human actions and provide efficient collaboration. To achieve this goal, we need new technologies that not only estimate the motion of the humans, but that fully describe the whole-body dynamics of the interaction and that can also predict its outcome. These hardware and software technologies are the goal of the European project AnDy.

In this paper, we describe the roadmap of AnDy, which leverages existing technologies to endow robots with the ability to control physical collaboration through intentional interaction. To achieve this goal, AnDy relies on three technological and scientific breakthroughs. First, AnDy will innovate the way of measuring human whole-body motions by developing the wearable AnDySuit, which tracks motions and records forces. Second, AnDy will develop the AnDyModel, which combines ergonomic models with cognitive predictive models of human dynamic behavior in collaborative tasks, learned from data acquired with the AnDySuit. Third, AnDy will propose AnDyControl, an innovative technology for assisting humans through predictive physical control, based on AnDyModel.

By measuring and modeling human whole-body dynamics, AnDy will provide robots with a new level of awareness about human intentions and ergonomy. By incorporating this awareness on-line in the robot's controllers, AnDy paves the way for novel applications of physical human-robot collaboration in manufacturing, health-care, and assisted living.

Keywords: robotics, wearable sensors, ergonomics, machine learning, prediction, anticipation, MSD, human movement, cobots, exoskeletons, humanoids

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1. Introduction

In modern societies, the demand for physical assistance to humans is increasing. In factories, for example, production workers execute repetitive tasks in non-ergonomic postures that, on the long run, often cause musculo-skeletal diseases. The increasing age of the workers poses additional risks for muscolo-skeletal accidents in physically demanding tasks. Many workstations are now equipped with co-bots sharing the workspace with workers. Despite the fact that the low-level control of these machines allows the humans to physically interact with them in a safe way, most workstations actually implement the concept of "human-robot co-existence", that is the robot and the human share the space, work side by side, but have very few limited interactions. Particularly, there is little "collaboration", that literally means "working together". If robots want to go beyond the mere "act" in a shared space, they must not only be proficient in physical interaction, but also in physical collaboration.

Not all (physical) interactions necessarily are collaborations. Collaboration is a higher and more cognitive form of interaction, where the two partners mutually understand each other, mutually predict and control the exchanged forces, posture and movements while being able to anticipate those of the other partner.

To fully describe the whole-body dynamics of humans collaborating with other humans, and humans collaborating with robots, we need new technologies that allow us to not only estimate the motion, but also to predict its outcome, so that the robots can properly react to the human actions and provide efficient collaboration. These hardware and software technologies are the goals of the H2020 European project AnDy (www.andy-project.eu).

The aim of this paper is to present the roadmap of the AnDy project, presenting the key methodologies and technologies that we will develop for tackling our ambitious objectives.

In AnDy, our requirement is to develop safe dependable robotic systems that are able to collaborate with people by predicting and anticipating their movements.
Having such skills requires understanding the biomechanics of collaboration, to have models that we can use to integrate cognition in the robot. To develop these models, we need to track and model the human whole-body dynamics motions.

However, current robotic technologies are not yet able to provide these measures in real-time: therefore robots have a blind spot. To predict the future forces and postures of the human, we need first a sensing device that can measure the human whole-body dynamics, which makes the robot aware of the entire human body posture. This is very different from the current cases where the robot only controls the

physical interaction with the human, and is thus aware of the human only at the contact level.
In other terms, the current limitations of robots in observing human dynamics makes them blind to the human dynamics, and "unaware" of the human effort, which leads to inefficient and non-ergonomic collaboration.

In AnDy, our first milestone is to resolve this blind spot, by developing a novel sensor suit, the AnDySuit, capable of measuring human whole body dynamics in real-time.
The big data sets collected with the AnDySuit will be used to generate ergonomic and anticipatory models. Those models will be used online by the robots to adapt their on-line control and make collaboration more efficient and ergonomic. It will combine wearable sensing technologies based on inertial sensors, EMG, tactile and force/torque sensors.

To evaluate the AnDySuit and its application for ergonomic human-robot collaboration, we devised three validation scenarios covering a wide spectrum of technical challenges in a crescendo of complexity. In the first validation scenario, the robot is an industrial cobot, which tailors its controllers to individual workers to improve ergonomy. In the second, the robot is an assistive exoskeleton that optimizes human comfort by reducing physical stress. In the third, the robot is a humanoid, which offers assistance to a human while maintaining the balance of both.In all three cases the robot leverages the measurements of the AnDySuit and the models to predict the intention, action and efforts of the human. This knowledge is the basis to develop novel controllers for efficient human-robot collaboration.

Further, the three scenarios with the three different robots (cobot, exoskeleton and humanoid) allow us to investigate the collaborative action and strategies of the robot in different contexts of manufacturing and industry, which increases the impact of our research.

2. Methods

The ability to collaborate with humans requires that the robots have the ability to provide physical assistance to people that needs help in performing a certain task. The fundamental assumption is that physical collaboration requires the robot to understand what the partner is doing and predict what the partner is going to do. This requires a model of the partner, and since we are not only interested in the motion but also in the effort, we need a comprehensive model that contains kinematics and dynamics information of the human.

Developing models requires observations, and to make appropriate observations to study a phenomenon often we need to create new tools. This paradigm is recurrent in our history since centuries: for example, the Newtonian telescope was used to observe celestial orbits, which led to the universal gravitation law. In a similar way, to develop anticipatory controllers that enable robots to collaborate with human partners (AnDyControl) we need predictive models of the human motion and dynamics (AnDyModel); to create these models, we need to collect observations of collaborating partners (AnDyDataset), with a novel tool (AnDySuit) that allows us to fully measure the kinematics and dynamics of the humans.

1.1 Key technologies

Methodologically, the concept above translates into four sequentially enabling objectives, which define our roadmap:

- The AnDySuit: this is going to be a breakthrough technology that allows us to fill the blind spot of measuring human-robot physical interaction. The AnDySuit is a wearable device that monitors in real-time the kinematics (position, velocity, acceleration at the joints/limbs) and dynamics of the human (contact forces, joint torques and muscle activations): that is, it provides the whole-body posture and whole-body dynamics. By processing the kinematics and dynamics measures, it allows retrieving important variables for collaboration, such as the contact stiffness, the gaze direction (here approximated by head direction), and for ergonomics, such as the body posture.

- The AnDyDataset: the AnDySuit will enable us to record the motion and dynamics of a human performing different tasks, of two humans collaborating, and of a human collaborating with the robot. The kind of recordings we will do are unique in their kind, as we will mix wearable inertial measures, force/torque measures, EMG, motion capture, etc. This will allow us to record kinematics descriptors of the actions (e.g., marker placement, estimated joint angles) as well as dynamics descriptors (e.g., contact force at the hands and feet, arm stiffness). Data collection will take place both in research labs and in real manufacturing scenarios. Experimental protocols with ethics committee approval will be obtained by the partners leading the data collection.

- The AnDyModel: the AnDyDataset will enable the development of models of human motion and dynamics and human collaboration. Accurate dynamics models will rely on the musculo-skeletal models of AnyBody, but model reduction and strong optimization will be obtain real-time signals. We aim at three different types of models: ergonomics models, that are used to retrieve relevant metrics for assessing the ergonomics impact of the motions, based on the metrics of the standard evaluation tools (e.g., EAWS, OCRA) (GLAESER et al., 2014); classification models, that are used to recognize the current activity of the human; and predictive models, that are used to predict the future evolution of the dynamics and motion of the human (e.g., the goal position of a reaching action, as well as the joint torques that are necessary to accomplish the movement). For the latter, we will explore different machine learning tools, ranging from probabilistic movement primitives to deep neural networks (DRONIOU et al., 2015).

— The AnDyControl: the final objective is to develop online control strategies for physical human-robot collaboration. Thanks to the AnDySuit, we can measure the human motion and its dynamics in real-time. These observations can be used to make predictions using the prior information provided by the AnDyModel, for example predicting the goal of a human movement, which forces or trajectories to expect. The AnDyControl here has the goal to adapt the robot control strategy in real-time, taking into account such predictions, with the purpose to optimize the collaboration, particularly the ergonomics criteria of the human movement.

The four objectives are summarized in Figure 1, which also represents the logical and temporal structure of the project and the interconnection between the objectives. The development of the AnDySuit is the first goal of the project, as it defines the main dependency for the dataset collection. Since it is mostly based on wearable sensing technologies that are already available on the market, it is reasonable to expect a high TRL (*technology readiness level*) for this device.

All the other objectives have a lower expected TRL, with the most ambitious predictive models and controllers for collaboration being those with the lowest.

The development of models and controllers will basically proceed in parallel, in a crescendo of complexity. In order to reduce the risks of a purely sequential methodology, we defined a number of sub-objectives at incremental levels of difficulty with respect to two main metrics that are particularly relevant for collaborative tasks: mutual-care and anticipation.

Mutual-care is related to the amount of care for the partner, i.e., the concern that the actor has for the partner (e.g., partner's equilibrium, partner's posture, partner's effort) in the collaborative task execution. In a situation of minimal care, the robot does not particularly care about the forces and postures that the human assumes during the collaboration. If the robot starts "caring" about the human, it means it takes into account human-related variables in the design of its control action. For example, it evaluates the ergonomics postures of the human during the collaborative task, to adapt its action to maximize the comfort of the human. To show better "care", the robot must then monitor the posture and forces in real-time, all along the collaboration, to react and optimize the collaborative action.

Anticipation is related to the amount of synchronization needed to successfully complete the collaborative task, and it is strongly related to the prediction capabilities of the robot. In a situation of minimal anticipation, the robot does not need to anticipate the human partner's positions or forces to perform the collaborative task. If the robot is capable of classifying and recognizing the current action performed by the human, it can choose appropriate control settings to adapt to each action/task. If it can recognize the goal of a reaching movement, or the intent of motion, it can proactively provide a support control action. If it is able to predict the positions and forces that the human partner will do, it can use this information to choose its future control actions and postures as well.

A sketch of the collaborative objectives in terms of the increasing levels of anticipation and mutual-care is shown in Figure 2. Interestingly, the complexity of models and controllers is reflected also in the type of robots used for demonstrating the collaborative tasks.

We stress on the fact that the collaborative scenarios will use the AnDySuit, which provides the online measurements of the human motion and forces, the AnDyModels to extract ergonomics metrics, predict the intentions and motions, and the AnDyController to provide suitable *human-careful* controllers.

The key difference with respect to previous projects is to provide technologies for human-aware and human-careful physical collaboration. *Human-awareness* refers to the fact that robot should be able to monitor human motions and forces. Human-care refers to the robot ability to provide a collaborative interaction that takes into account the human needs (e.g. ergonomic posture, minimal fatigue, equilibrium maintenance). In the literature, most prior works dealing with collaboration provide prediction (i.e. human-awareness) but often with limited human monitoring. Very often human-robot interaction is modeled as an exchange of forces, without explicitly modeling neither the human posture, nor the human joint torques. For example, in the manufacturing domain often only the contact forces or the forces at the end-effector are considered. In the healthcare domain, exoskeletons typically access the human posture and exchanged forces (eventually projected into joint-torques) but this information is always local (i.e. limited to body parts where the exoskeleton is attached); the remaining body postures and forces are often neglected. Few projects have been focused on the importance of monitoring human body posture, typically measured with depth sensors (e.g. kinect) or wearable devices (e.g. the Xsens MVN). In this sense, in AnDy we put forward the concept of "*human-careful*", as opposed to simple "*human-aware*", meaning that the robot takes into account the whole body measures from the human in the synthesis of its collaborative strategies.

In this sense, the AnDySuit is going to be a breakthrough technology that allows us to fill the blind spot of measuring human-robot physical interaction. This wearable device that monitors in real-time the kinematics (position, velocity, acceleration at the joints/limbs) and dynamics of the human (contact forces, joint torques and muscle activations): that is, it provides the whole-body posture and whole-body dynamics. By processing the kinematics and dynamics measures, it allows retrieving important variables for collaboration, such as the contact stiffness, the gaze direction (here approximated by head direction), and for ergonomics, such as the body posture. These quantities will be used by the robots to optimize their control strategies, with the aim to provide ergonomically safe actions for the human partners. By optimizing human-related metrics, we will realize a human-careful control.

3. Results

The achievements of the project will be experimentally evaluated on different robotic platforms, addressing different collaborative scenarios.
Three types of robots are addressed in AnDy: collaborative robotic manipulators, or "*cobots*", exoskeletons and humanoid robots.
Cobots are already diffused in manufacturing, and so far have been mostly used in co-existance scenario where human operators share the same workspace of the robot, working side-by-side or performing tasks in coordination. For these robots, performing more collaborative tasks is an innovation requiring the online ergonomics estimation of the human partner. The main cobots we will use in AnDy are the KUKA iiwa and LWR.
For exoskeletons, the main problem we will address is how to adapt control settings to the action of the human operator in a smooth and automatic way. An interesting research is the quantification of the effects of the action of the exoskeleton on the human body, which requires the measure of kinematics and dynamics of the human thanks to the AnDySuit. The main platform we will use in AnDy is an exoskeleton for overhead work by Ottobock.
Humanoids robots, especially legged robots, are still research prototypes. However, in the future it is reasonable to expect that humanoids will find their use in manufacturing, in applications where *cobots* or even manipulators mounted on a mobile base would not be able to perform the desired tasks.

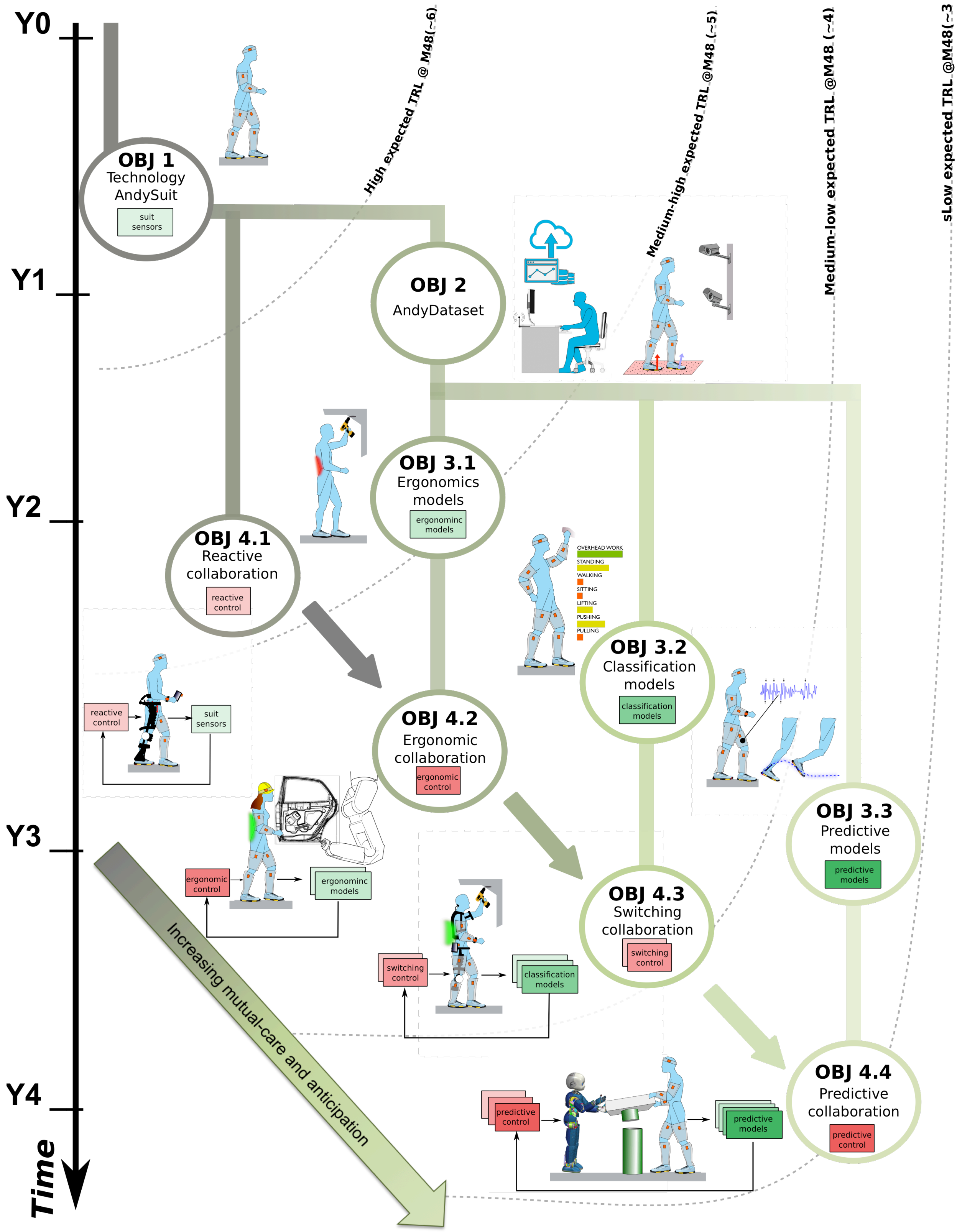

Figure 1: [Notice: this figure may be difficult to interpret if not printed/visualized in colors] A sketch of the roadmap of the AnDy project and its objectives.

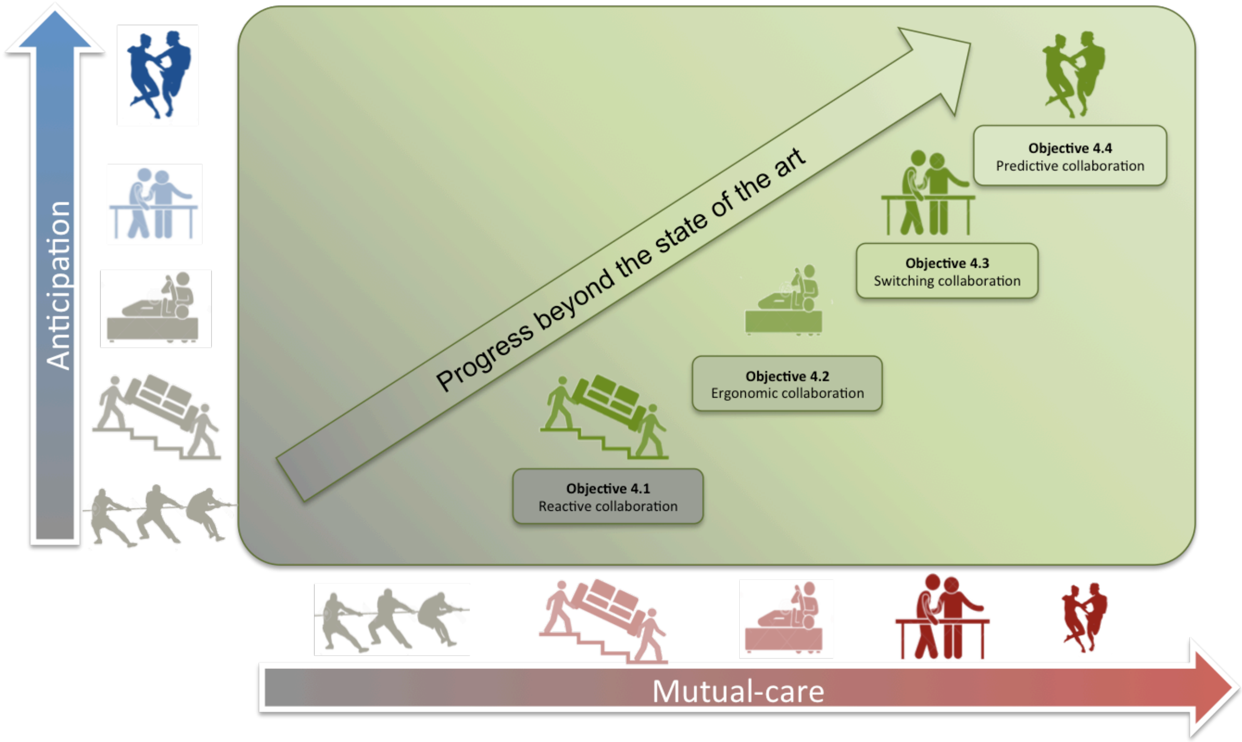

Figure 2: [Notice: this figure may be difficult to interpret if not printed/visualized in colors]. A sketch of the collaborative control objectives, with respect to the different levels of mutual-care and anticipation, used as metrics for collaboration.

The three collaborative scenarios with the three types of robots are represented in Figure 3.

Figure 3: the three collaboration scenarios with the three different robot types: *cobot* or robotic manipulator, exoskeleton and humanoid robot.

Some European projects are currently focused on producing new humanoids for aircraft manufacturing (H2020 COMANOID – http://comanoid.cnrs.fr) and for technical support (H2020 SECOND HANDS – http://secondhands.eu). In our project, we will use the humanoid robot iCub, which is equipped with force and tactile sensing and allows us to tackle the scientific challenges of collaborative human-humanoid interaction.

1.1.1 Scenario 1 (cobots)

A key feature of collaborative robots / cobots in assembly is that they share a workspace with human workers. Important distinctions between different types of cobots are whether they avoid or exploit contact with humans, and whether they are purely reactive or also predictive (HADDADIN et al., 2008; HADDADIN et al., 2012). In contrast, SISBOT et al. (2010) generate motion plans that take human social rules into account. DRAGAN et al. (2013) plan motions such that they become easier for humans to interpret. Kinesthetic teaching exploits human-robot physical contact by enabling humans to demonstrate motions to robots by physically moving the (passive) robot (STULP et al., 2013). Virtual guides also enable human-robot contact, by constraining the motion to certain pre-defined trajectories or regions (RAIOLA et al., 2015).
Dynamic, active physical interaction between a human and a robot is particularly challenging. AnDy enables this by 1) giving direct, on-line measurements of the human posture and forces exerted by the human through AnDySuit; 2) by not only reacting to, but also predicting human motion with AnDyModel by analyzing previous executions of tasks stored in AnDyDataset; 3) by taking the ergonomy of the human into account whilst generating motions. Monitoring humans with the AnDySuit will also facilitate the task of programming force-controlled robots for complex assembly tasks. At present the cost of cobots and associated programming is not cost-effective for small production lots (e.g. SMEs) and to flexible and customized productions. ANDY will enable force-controlled assemblies through collaborative human-cobot assemblies that will be more flexible, easier to customize and in the end more cost effective and suitable for SMEs.

1.1.2 Scenario 2 (exoskeletons)

Robotic assistive devices (i.e. exoskeletons) are being developed to either augment the abilities of able-bodied humans or to improve the condition of the people with impaired physical abilities (RAHMAN et al., 2006). Such devices assist movement abilities of different body parts (reviewed by DOLLAR et al., 2008). The purpose of such devices is to provide useful mechanical power by operating synchronously with the person that is wearing it (GAMS et al., 2013). The human robot interface is crucial for a safe and comfortable interaction with an exoskeleton device (de ROSSI et al., 2011).
From the technical perspective there are two branches of exoskeleton development: passive power assist devices and active power assist devices. In general, active power assist devic-

es are more powerful, but require actuators and power source, which make them quite heavy; they can be found mostly in rehabilitation, orthopedics, assistive devices (YAMAMOTO et al., 2004; KAWAMOTO et al., 2005). On the other hand, passive power assist devices are mainly used to reduce the burden of the user rather than to amplify their forces (IMAMURA et al., 2011; WALSH et al., 2007).

One of the crucial elements of active assistive robots and exoskeletons are the actuators. A promising alternative to conventional stiff actuators is the use of elastic elements to create an intrinsic compliant behavior. This allows a safer human-robot interaction, shock absorbance, and leads to a greater energy efficiency than stiff actuators (VANDERBORGHT et al., 2012). An expansion of compliant actuators is variable stiffness actuators (VSAs) that allow changing the stiffness of the driven joint. These actuators fit the requirements of certain bio-inspired robots, since humans use the ability of changing joint stiffness to change, for example, the walking speed (KIM et al., 2011), and to accommodate changes in surface stiffness during walking (FERRIS et al., 1998). VSAs can, in principle, be used to extend the versatility of spinal support systems.

Today, especially for the assembly of heavy or bulky parts, weight compensators/balancers are used. Since these systems do not compensate for inertial forces, even small mistakes lead to work-related injuries (lower back pain, spine injuries) (KROEGER et al., 2009). In this context, AnDy will establish a novel paradigm for ergonomic interventions through a combination of the four interrelated technologies (AnDySuit, AnDyDataset, AnDymodel and AnDyControl). With AnDy the workers working in human-unfriendly environments will get a valuable assistant that will make their job safe from the possible injuries. The solutions in AnDy also have high potential to become an indispensable diagnostic tool for specialists working in physical medicine and rehabilitation, occupational medicine, and others. A driving force behind the efforts in this scenario is the fact that musculoskeletal problems account for the largest part of work incapacities and that there is a clear demand for solutions that would mitigate these problems. Our project will utilize such sensory solutions (i) to develop models for studying loading of the human joints and then (ii) to leverage exoskeleton control principles and create solutions that will allow a natural merge of exoskeleton technology with the vast spectrum of available sensory solutions.

Moreover, the control strategy developed in AnDy for the exoskeletal system will smooth the breakthrough of human-exoskeletal interaction in the field of wearable/assistive robots that support workers in a variety of tasks. Our goal is to improve working ergonomics with prevention of muscle skeletal disease, which will have a direct influence on improving the quality of manufacturing and related processes with special attention given to the ageing workforce. To make sure that the innovation potential of this scenario is as high as possible, user-acceptance and cost-effectiveness will be also addressed.

1.1.3 Scenario 3 (humanoid robots)

In the human-humanoid interaction experiments with the iCub performing collaborative assembly with 56 adults, IVALDI et al. (2017) gained a lot of knowledge about the dynamics of social signals and physical signals (e.g., contact forces). However, in these experiments switching control strategies to adapt the compliance were controlled by the human and there was no prediction of human intent. On the other hand, in the CoDyCo project there have been numerous advancements in the whole-body interaction of the iCub with its environment (NORI et al., 2015), also with humans perturbing the robot equilibrium. There is a need to make the two research streams converge for the case of collaboration. This convergence should happen at several levels: first at the control level, as the robot should be able to cope with the contact forces; second, at the prediction level, as the robot should extract information from the haptic exchange. The first problem is about how to switch between controllers where contact forces must be rejected or followed, which are about functional roles. Traditionally, many works adopted a conservative approach of assigning the robot a passive follower role, e.g. implemented with a low-level impedance control loop in pHRI. Based on fixed roles (master/slave, leader/follower), the robot can easily estimate the human intention and improve the collaboration (GROTEN et al., 2010). Extracting information from haptic signals has been addressed in several papers using local force/torque sensing (BUSSY et al., 2012; BERGER et al., 2013); however, DUMORA et al. (2012) noted that wrench measurements provide incomplete information to detect the operator's intent of motion, which was confirmed by REED (2012). Haptic feedback can temporarily be sufficient to achieve subtasks, if contextual information about the task phase is provided. However, more non-verbal cues, e.g., gaze, may be necessary to recognize the partner intent during collaborative tasks and synchronize the dyadic activity (IVALDI et al., 2014). Humanoid robots such as the iCub are well poised to investigate these issues.

In AnDy, we want to exploit the humanoid to push further the complexity of the collaboration. First, the humanoid will be balancing on its feet, therefore it will have to carefully control the exchanged forces and anticipate the human forces to prevent falling; there will be a bilateral control action in place, and the robot will need to balance the control strategy between leader and follower, predicting the human action. Finally, the human and the humanoid will have to realize a complex assembly action, for example a collaborative carrying or a snap-fit. As in the other scenarios, the AnDySuit provides the human posture and dynamics, AnDyModel provides models of human motion: the AnDyControl here is pushed to a bigger level of complexity. From the robot control point of view, this task explores the trade-off between physical interaction and postural tasks when the robot balance is at stake. Control strategies mixing soft and hard priorities will be considered and combined with suitable learning strategies to cope with uncertainties, following previous results (NAVA et al., 2017; MODUGNO et al., 2016). Furthermore, this task allows studying whole-body control strategies for humanoid robots with several tasks and several constraints (some from the human, some from the humanoid, some originated by the closed-loop chain formed during their collaboration) in presence of partial and noisy observations of the state.

4. Conclusion

The H2020 European Project AnDy started in January 2017 and lasts 4 years. The goal of AnDy is to endow robots with the ability to control physical collaboration through intentional interaction. To achieve this goal, AnDy relies on three technological pillars: a wearable sensing device, called AnDySuit, which tracks the human motions and forces; AnDyModel, that is ergonomic and human movement models that also provide prediction of movement in collaborative tasks; AnDyControl, which combines ergonomic models with cognitive predictive models of human dynamic behavior in collaborative tasks, learned from data acquired with the AnDySuit.

In this paper, we described the roadmap of the project, its motivation and its objectives. As described in the previous section, the research outlined in the roadmap builds on prior results from the different partners, such as the learning and control frameworks developed in the last years in the framework of the European Projects CoDyCo (https://www.codyco.eu/) and Spexor (http://www.spexor.eu/), for humanoid robots, cobots and exoskeletons.

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