Clothes Perception and Manipulation

D1.1
Scenarios and detailed specification of M12 demonstration

Version: 1.1
Last Update: May 30, 2012

Distribution Level: PU (Public)

The research leading to these results has received funding from the European Communitys Seventh Framework Programme (FP7/2007-2013) under grant agreement n^o 288553

SEVENTH FRAMEWORK PROGRAMME

Project Number	:	FP7-288553
Project Title	:	Clothes Percpetion and Manipulation

Deliverable Number	:	D1.1
Title of Deliverable	:	Scenarios and detailed specification of M12 demonstration
Nature of Deliverable	:	Report
Dissemination Level	:	Public
Version	:	1.1
Contractual Delivery Date	:	Apr 30, 2012
Actual Delivery Date	:	May 30, 2012
Contributing WP	:	WP1
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Abstract

The aim of this deliverable is to specify further the Month 12 demonstration of the *CloPeMa* project, with respect to the Description of Work. Much of the *CloPeMa* first year efforts will be spent on establishing the experimental platform (dual-arm robot system), develop methods and competencies at each partner site, and starting real cooperation between *CloPeMa* partners. The Month 12 demonstration should prove that *CloPeMa* partners reached the state-of-the-art level by mimicking capabilities demonstrated by others, i.e. pick a towel from a table and fold it.

To bootstrap research activities, the tasks of the Month 12 demonstration scenario is broken down into relatively independent competencies to be provided by project partners.

A part of this deliverable is devoted to the review of the related state-of-the-art, including literature in sensing, perception, manipulation and planning related to soft materials, such as textiles or garments. Several industrial application scenarios are presented as well. The report, finally, discusses the limitations of the state-of-the-art and highlight existing challenges that have to be confronted during the project.

Keywords

garment manipulation, grasping, sensing, perception

Revision History

Version	Description	Author(s)	Date
0.5	First draft, including contribution by partners	UniGe	9 May 2012
0.9	Updated introduction and scenario specification	CVUT, CERTH, UniGe	21 May 2012
1.1	Last draft	UniGe	30 May 2012

Contents

1 Introduction

The goal of *CloPeMa* is the development of a dual-arm robot system with the cognitive abilities allowing to perceive and manipulate textiles and garments in unstructured environments. Clothes of previously unknown shape and structure will be picked from a pile or container, untangled and spread for some industrial process (joining, finishing, etc) or folded. These behaviors are more complex than recent work by others because they involve handling clusters of clothes [76] and do not require a known background and cloth geometry [40] or predefined folding manoeuvres [69].

To realize these goals, a fast and sensitive perception system will be developed that combines vision, range finding, and tactile sensing. There is a need for novel representation of the robot 'world' allowing fusing senses and reasoning. This multi-modal sensing strategy will increase the confidence in measurements and hypotheses about the structure of the fabric and the environment by introducing feedbacks. The reasoning and planning module will generate these hypotheses and will guide the saliency of the sensing system to efficiently extract only the important features from the environment. The reasoning module will also guide the robot's movements, which will in turn be exploited to explore new sensing capabilities. The tactile hands will provide direct sensory information from the robot's movements while the perception-action cycle will generates an indirect form of sensory feedback.

The main scientific novelty of this project is the proposed close integration of perception (tactile sensing with visual sensing), action (two-handed manipulation), and reasoning on various levels of abstraction. This is expected to allow functionalities that had hitherto proved elusive for systems using only some of these parts. The perception-action cycle methodology will enable the robot to operate in an a-priori unknown environment.

Compared with other international efforts, *CloPeMa* has equally ambitious objectives as the ARM (Autonomous Robotic Manipulation) program in the US, although in the narrower field of cloth perception and manipulation.

The main challenges involved in achieving the aforementioned objectives stem from the high flexibility, uncertainty and variability of clothes.

Textiles, do not have a stable shape and cannot be manipulated on the bases of a priori geometric knowledge. In general, grasping of limp materials is characterized by partial observability. Picking is made uneasy by the tendency to flatten under gravity. It is difficult to assess the stability of a grasp. Attention must be paid to the tension created by grasping, which affects the apparent shape of the material and may influence the recognition of what an object is and which part of the object is grasped.

Physical modeling of clothes has only been investigated by the computer graphics community, aiming at realistic rendering. *CloPeMa* does not intend to follow the physical modeling path similarly as humans do not do.

The aim of this deliverable is to specify further the Month 12 demonstration of the *CloPeMa* project with respect to the Description of Work. Much of the *CloPeMa* first year efforts will be spent on establishing the experimental platform (dual-arm robot system), develop methods and competencies at each partner site, and starting real cooperation between *CloPeMa* partners. The Month 12 demonstration should prove that *CloPeMa* partners reached the state-of-the-art level by mimicking capabilities demonstrated by others, i.e. pick a towel from a table and fold it.

To bootstrap research activities, the tasks of the Month 12 demonstration scenario are broken down into relatively independent competencies to be provided by project partners.

A part of this deliverable is devoted to the review of the related state-of-the-art, including literature in sensing, perception, manipulation and planning related to soft materials, such as textiles or garments, section 2. Furthermore, several industrial application scenarios are also presented.

Due to the interdisciplinary nature of the research we split prior work to different topics, such as sensing, perception, manipulation and planning. In section 3 we discuss the limitations of the state-of-the-art and highlight existing challenges that have to be confronted during the project.

For the first year a relatively simple scenario was chosen as a guideline. The involved tasks in the scenario have been broken down into individual competencies. They will be demonstrated independently by partners and the initial integration will be performed. The involved competencies are elaborated in section 3. Finally in section 6 we propose a series of short term industrial applications of *CloPeMa*.

Partners will have to dedicate significant efforts to build *CloPeMa* experimental platform. The robots seem to be delivered to partners at Month 5 or Month 6 of the project. Partners have to familiarize with the chosen middleware and start connecting their modules to the system. This will take some time. We expect that the Year 1 scenario will be performed at CVUT site because the partner responsible for integration (NEO) will experiment at *CloPeMa* experimental platform at CVUT.

2 Research and Industrial State of the Art

2.1 Related projects

ROBOSKIN – is an integrated project, May 2009 till April 2012. It develops and demonstrates a range of new robot capabilities based on robot skin tactile feedback from large areas of the robot body. The focus is part on the investigation of methods and technologies enabling the implementation of skin sensors usable with existing robots. Part on the development of new structures for representing and integrating tactile data with existing cognitive architectures, supporting skin-based cognition, behavior and communication.

NIFTi – is an integrated project, January 2010 till December 2013. It aims at human-machine cooperation in rescue robotics. Demonstrator is built around a track-propelled mobile robot rich in sensors. CVUT is responsible for computer vision and pattern recognition functionalities. In addition, a good deal of experience has been learned by CVUT in integration on top of ROS and in robot navigation and planning.

HUMAVIPS – is STREP, February 2010 till January 2013, aiming at audio-video interaction demonstrated on a 55 cm tall humanoid robot NAO. CVUT is responsible for computer vision and pattern recognition functionalities.

MASH (Massive Sets of Heuristics) – is a STREP, January 2010 till December 2012, creates new tools for the collaborative development of large families of feature extractor. Users can use the web interface to run experiments remotely on a testbed placed at CVUT. It consists of an industrial robot arm and a LCD monitor screen on which various backgrounds can be simulated. The camera observes this scene and the system manipulated object on this cluttered background. CVUT experience relevant to *CloPeMa* is the installation and the control of the robot, maintaining cameras, etc.

Other relevant EC funded projects

STIFF – Biomorphic Variable Stiffness, January 2009 till December 2011. Its aim is to equip a highly biomimetic robot hand-arm system with the agility, robustness and versatility that are the hallmarks of the human motor system, by understanding and mimicking the variable stiffness paradigms that are so effectively employed by the human central nervous system. A key component of our study will be the anatomically accurate musculoskeletal modelling of the human arm and hand.

VIACTORS – Variable Impedance ACTuation systems embodying advanced interaction behaviORS, Feb 2009 till Jan 2012. This project aims at developing and exploiting actuation technologies for a new generation of robots that can co-exist and cooperate with people and get much closer to the human manipulation and locomotion performance than todays robots do.

LEAPFROG – Leadership for European Apparel Production From Research along Original Guidelines. 6th Framework Programm, May 2005 till April 2009 was a big integrated project. The aim in the Research module B, named Automated Garment Assembly, relevant to *CloPeMa* was a family of innovative metamorphic grasping devices for dexterous, effective and robust handling of limp materials (fabric). UniGe participated in this activity and the LEAPFROG results are in its background knowledge.

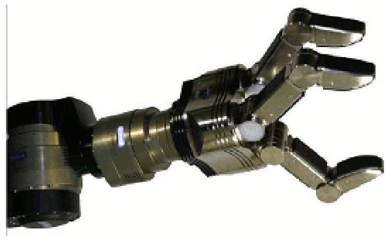
The Hand Embodied – is an integrated project, March 2010 till February 2014. Its aim is to study how the embodied characteristics of the human hand and its sensors, the sensorimotor transformations, and the very constraints they impose, affect and determine the learning and control strategies we use for such fundamental cognitive functions as exploring, grasping and manipulating. The robotic hand is to be developed by DLR, Germany. The haptic component is lead by the Pierre et Marie Curie.

DEXMART – 'DEXterous and autonomous dual-arm/hand robotic manipulation with sMART sensory-motor skills: A bridge from natural to artificial cognition' – is an integrated project, February 2008 till January 2012. The project concentrates on personal and service robotics where dexterous and autonomous dual-hand manipulation capabilities are required. The experiences from this project have been published in the edited book [60] in April 2012.

Other projects

Uni Karlsruhe project SFB-588, Learning and cooperating multimodal robots is a large German national initiative. Two subprojects, at least, are relevant to *CloPeMa*.

The first project is ‘Intelligent control systems and reactive grasping skills for industrial Multi-fingered gripper SDH2’. It is the IPR cooperation treaty, which started in November 2008. The aim is the development of software modules to facilitate the integration of a Multi-fingered gripper in real industrial applications. The SCHUNK DextrousHand 2.0 is used in experiments.



The second project is ‘Touching and Grasping’ and examines lightweight and flexible hands for a humanoid robot. The contributions include a position and force-torque control and the optimization of the gripping patterns based on grasp pattern database. At a higher level, the subproject considers the extension of exploration and grasping abilities, the study of exploration strategies and experience-based grasping. The recognition based on haptic information is in [19].

Robot folding a T-shirt, Dartmouth College, Computer Science Department, USA. Matthew Bell in 2009 put a wand into robot gripper and used it for folding a T-shirt in a very simple way without much sensory feedback. The approach is not adaptive to a varying set up, of course. Results are summarized in Bell’s PhD thesis [4] from February 2010.

Hierarchical Decision Making for Physical Agent - U.S. National Science Foundation Award #0904672 for University of California-Berkeley, July 2009 till June 2013, part of this research is [40] which is very relevant to *CloPeMa*.

2.2 Hands & grippers, sensors

2.2.1 Human hands gesture in handling

Human Grip

According to [18] Goldfield, Napier (1980) distinguishes two classes of hand movement, prehensile and non-prehensile. Prehensile movements are those in which an object, fixed or free, is held by a gripping or pinching action between the digits and the palm. Non-prehensile movements of the whole hand include pushing, lifting, tapping and punching movements of the fingers.

A widely held functional taxonomy for prehensile movement of precision and power grips, respectively (fig.1), is based upon the possible postural configurations that result from opposition between the terminal pad of the opposed thumb and the pads of the fingertips for the precision, and between the surface of the fingers and the palm with the thumb acting as a ”buttress” for the power grips.

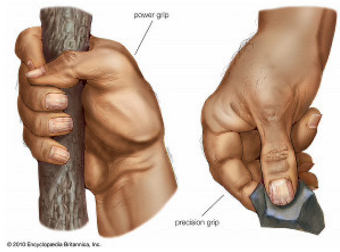


Figure 1: Hand: power and precision grips

In 1998, Tubiana and other authors, in the book ”Examination of the hand and wrist” [67] elaborated the definition about human grip as following:

- Power grip (digitopalmar grip) for grasping depends essentially on the movements of the fingers opposing the palm.
- Precision grip (thumb-finger pinch) requires, as a minimum, active contact between the thumb and a digit, and the mobility of the thumb and an opposing finger, usually the index. The pinch can be terminal, the distal phalange flexed or subterminal pulpar, with the distal phalange extended (fig.2).

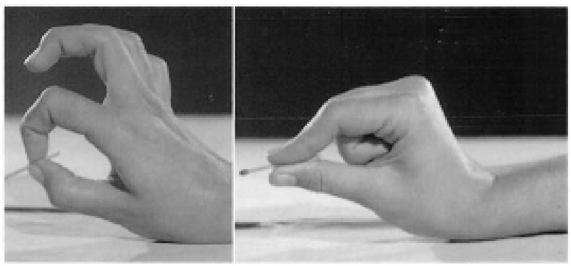


Figure 2: Terminal (left) and Subterminal (right) pinch.

- The lateral pinch requires only the mobility of the thumb ray (fig.3). One of the most useful forms of this mechanisms in lateral pinch is between the thumb and lateral border of the index finger. This is also the easiest to reconstruct surgically.

The contribution of the middle finger is also mentioned. The adjunction of a third digit to the grip brings more precision (fig.4).

Gripping force

Contact force, such as touching, gripping, and grasping, has been studied for a couple

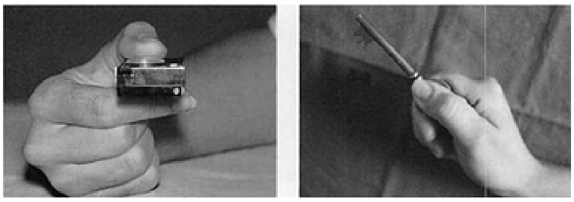


Figure 3: Lateral pinch.

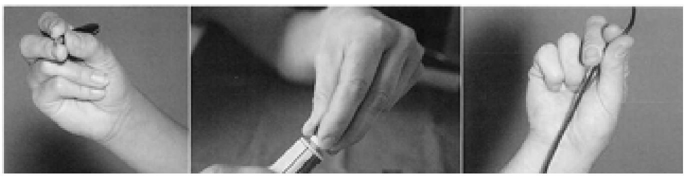


Figure 4: Precision grip with the support of the third digit

decades. However, because of the cross-field property, it is very difficult to define the quantitative value for this type of force.

While researching about external finger force, Radwin [53] group designed an experiment (fig.5) to understand the individual force of each finger in sub-maximal static pinch depended on the total force, the load and the pinch spans. The average contribution of the index, middle, ring and little fingers are 36%, 26%, 20% and 19%, respectively, for the static lifting task.

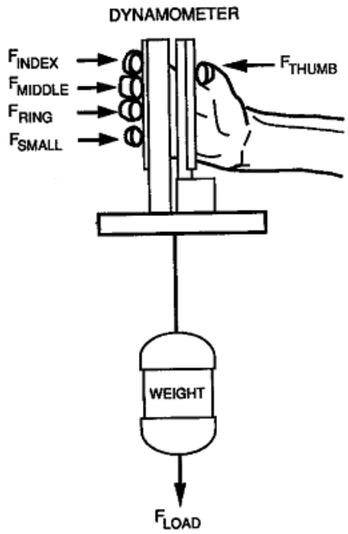
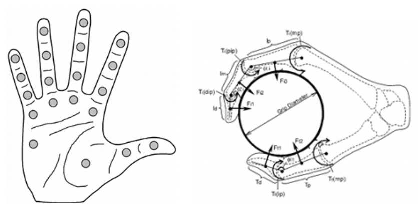


Figure 5: Experimental apparatus of Radwin [53].

In another experiment of Kargov [14] and his colleagues, a cylindrical object is held with a power grasp and the contact forces are measured at 20 predefined positions, as shown in fig.6. During this experiment, three upper limp-deficient persons used a System-Electro-Hand^{TM} with a maximum grip force of 90N at the fingertips. Another five subjects



(a) (b)

Figure 6: Positions of 20 FSR (Force Sensitive Resistor)sensors (a) and the orientation of contact forces (b)

used a Sensor-Hand^{TM}. Both systems were from the same manufacturer Ottobock[1]. The grip force distributions, as presented in fig.7 and tab.1 and the computed joint torques were compared between standard electric prostheses (in a experimental protheses with an adaptive grasp) and human hands (as a reference).

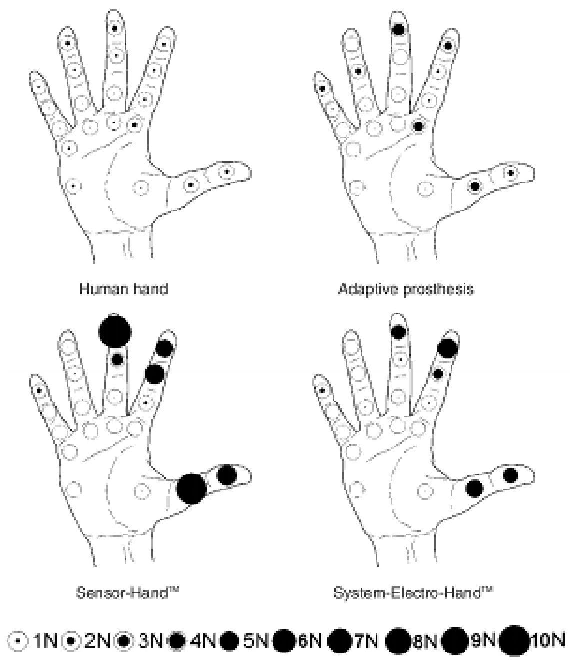


Figure 7: Contact force of the natural hand, the adaptive prothesis, and the two types of non-adaptive protheses.

Human hand gesture in exploration

Humans are remarkably successful at haptically identifying and learning about object. People have been researching about hand gesture in object exploration and handling for years. They are trying to classify the motions of the hand and the information that we can obtain from them.

Cutkosky and Howe, in one of their papers [43], presented the grasp taxonomy in

[1]http://www.ottobock.com/

	Average force [N]	Maximum force [N]	Sum of forces [N]	Force at fingertips [N]
Human hand	0.8(0.7)	3.8	16.7	6.3
Adaptive prothesis	1.3(0.4)	4.7	21.3	9.9
System-electro-hand™	2.6(2.7)	13.8	28.5	17.3
Sensor-hand™	3.9(4.6)	24.7	47.4	24.9

Table 1: Force characteristics of different hand types

Finger	Kargov 04 d = 57mm m = 522g	de Castro 00 d = 50mm m = 400 - 600g	Radwin 92 d = 45 and 65mm m = 1000g
Thumb	1.3N	2.8-4.5N	nn
Index	1.0N	1.8-3N	5.7N
Middle	0.9N	1.8-3N	3.8N
Ring	0.8N	nn	2.9N
Small	0.4N	nn	2.6N

Table 2: Average force at the fingertips during sub-maximal static grasp.

which the grasping action is divided in small categories according to the function. The relation between dexterity, power, object size, etc. was also discussed. It is shown that, the smaller the object size the more precise the grasp is, especially in the thumb-index finger grasp type.

In terms of haptic understanding, Klatzky and Lederman [32] synthesize the knowledge about objects, based on the exploration procedure. In fig.8 all the attributes of the object that could be collected by the relevant exploration procedure are presented.

2.2.2 Hand mechanism

A gripper is a fundamental component in the robotic work cell. In the current offer of market-ready industrial grippers there exist a lot of products suitable for handling rigid objects. The handling of non-rigid materials, like fabric, is up to now a challenge faced more on academical than on industrial level. Currently used grippers, designed for fabric handling, are usually based on air-jet, vacuum, needle or adhesive grasping methods [66, 58]. Mainstream research in this area tries to develop a work cell targeting at robotic assembling for garments or shoe industry. Research work recently done by the European project Leapfrog used this traditional and some alternative fabric grasping devices, mounted on a highly adaptable gripper. The latter is designed to grasp pieces of fabric with very different shapes prepared on the cutting table and moved to the sewing machines position hang on an adaptable clamp.(fig.9).

For garment handling tasks, like sorting, folding and unfolding, the human hand is the basic template. Medical hand prosthesis or fully anthropomorphic robot gripper, although they have a good grasping performance [39, 9, 1], they present increased structure and control requirements complexity, in case we want to mimic human movements. The study of human gesture, used to work with clothes, sets out the movement required to

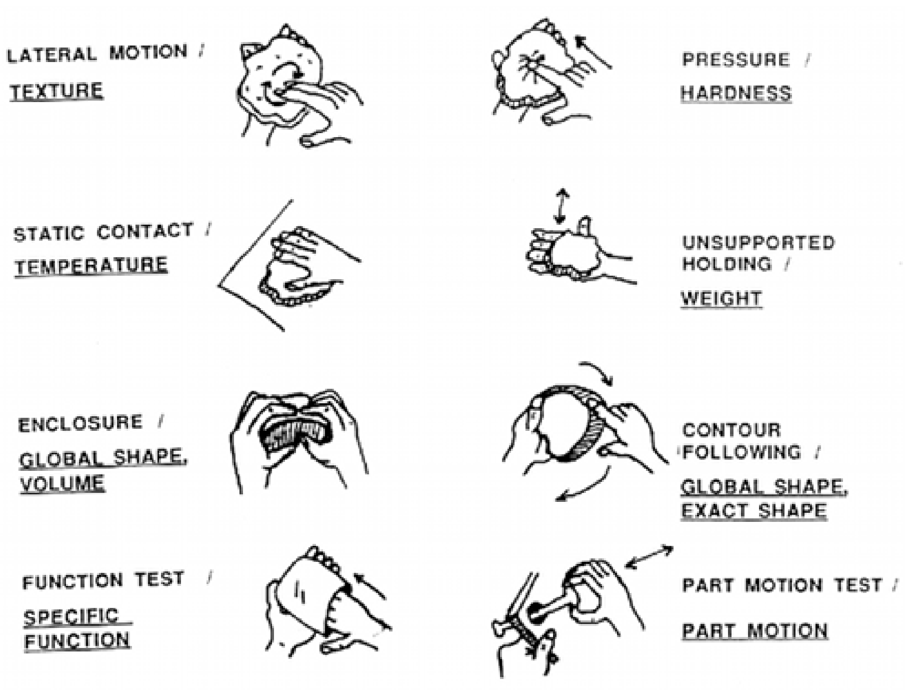


Figure 8: Haptic exploration procedures and the object attribute(s) with which each is associated [32].

Figure 9: Overall view of the Leapfrog Reconfigurable Grasping Device with the air-flow subsystems.

perform various tasks. Limiting the DOF and actuators quantity of the gripper to allow exactly only these movements it is possible to highly reduce the gripper's mechanical structure complexity and in this way we reduce control problems as well and in the same time we can maintain the required dexterity for handling. For example the gripper of Kirill Emantaev [16], designed and prototyped for his doctoral thesis, has only three actuators and a particular choice of construction materials. It is an anthropomorphic under-actuated hand with fingers moved by tendons. The main structure of the hand is a rubber sheet in approximate shape of full opened human hand, with the mechanism part simply glued in particular positions in order to allow the intended geometry of movements. In this way, he has reached a reduction of production costs hardly comparable for an artificial hand with so high level of grasping dexterity(fig.10). Another similar under-actuated anthropomorphic gripper proposed by [20] has 15 DOFs and a single actuator. The under-actuated mechanism moved by tendons, leaves space needed for embedding sensors. Industrial examples, notable for providing space needed for the integration of sensors and real usefulness of their feedback are the recently released Schunk grippers (fig.11).

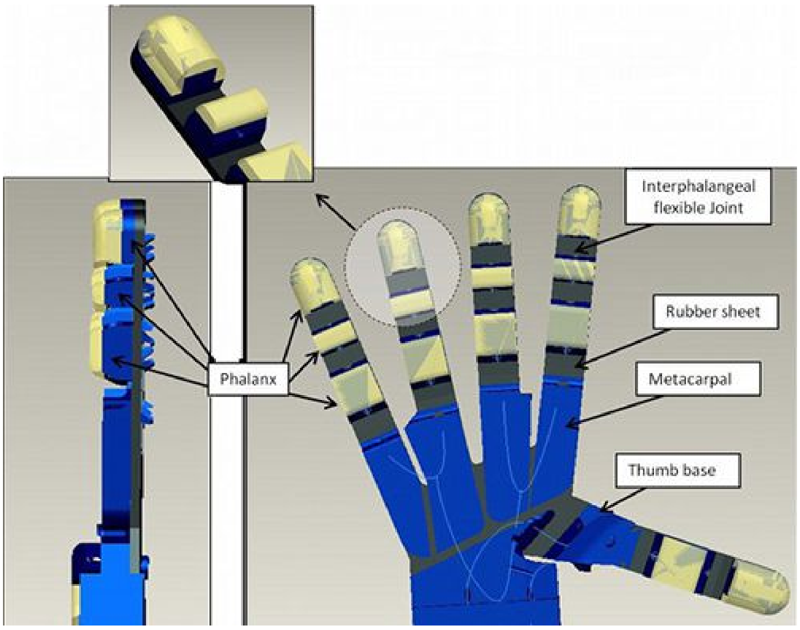


Figure 10: General view of the prototype of Kirill Emantaev hand.

Figure 11: SCHUNK SDH-2 with tactile sensors measure forces and torques.

2.2.3 The sensing system

In order to allow robots to interact with objects and the environment, tactile sensing is crucial. Indeed it has been widely investigated, as reported in [72], [35] and [12]. If we consider the hard task of discriminating and recognizing objects, a tactile sensor must allow not only to detect if there is a contact between robot and an object, but also to detect the physical characteristics of that object: texture, heat flow, mechanical properties. Texture is implemented as protrusions or undulations on the surface of the material that manifests as forces changes while the sensor translates across the surface [47]. This particular feature may allow to distinguish between different types of fabric on the basis of tissue structure and yarn dimensions. With regard to texture discrimination, Hosoda et colleagues [23] present an anthropomorphic soft fingertip in which there are randomly distributed strain gauges and PVDF film. Since the receptors are randomly distributed in the soft fingertip, the designer cannot map the physical phenomenon with the receptor outputs explicitly, therefore the robot has to learn the mapping through its own experience, and to organize the outputs of receptors. The sensor can distinguish between wood, paper, cork, and vinyl.

In [56] a novel tactile sensor is designed; it consists of two static elements (for x and y directions) made by piezoresistive foil sensors that yield position and force signals, which are surrounded by 16 dynamic sensor elements. These elements are obtained by two round capacitor membranes on which there are attached 30 fibers; thanks to the flexibility of the fibers it is possible to sense vibration and so to distinguish between object texture and to detect contact.

In the work of Deboissieu et al. [6] a three-axial MEMS-based force sensor is demonstrated, packaged as an artificial finger, with a hard structure for the bone and a soft rubber for the skin. The sensor is able to sense the periodic structure of fabrics or to differentiate papers from fabrics calculating a friction coefficient while sliding on a surface. A MEMS based capacitive tactile sensor array that is able to discriminate from coarse to fine textures (with feature spacing down to 0.2 mm) is proposed by Muhammad 2011 [48]. The availability of the tactile sensors array allows a combined spatiotemporal approach for the discrimination of textures, by considering the spectral content of each single sensor output and the variation in responses of spatially located sensors.

Jamaly and Sammut [24] built a finger like Hosoda [23] with randomly distributed strain gauges and polyvinylidene fluoride (PVDF) films embedded in silicone. In this paper it is shown how different textures induce different intensities of vibrations in the silicone and consequently, textures can be distinguished by the presence of different frequencies in the signal. To do this, a machine learning algorithm is presented for distinguishing between textures such as carpet, flooring vinyls, tiles, sponge, wood, and polyvinyl-chloride (PVC) woven mesh with an accuracy of $95\% \pm 4\%$ on unseen test data.

A method for interactive surface recognition and surface categorization by a humanoid robot using a vibrotactile sensory modality is proposed by Sinapov et al. 2011 [61]. The robot was equipped with an artificial fingernail that had a built-in three-axis accelerometer. The robot interacted with 20 different surfaces by performing five different exploratory scratching behaviors on them. Surface recognition models were learned by coupling frequency-domain analysis of the vibrations detected by the accelerometer with machine learning algorithms, such as support vector machines (SVM) and k-nearest neighbors (k-NN). The results show that by applying several different scratching behaviors on a test surface, the robot can recognize surfaces better than with any single behavior alone. The robot was also able to estimate a measure of similarity between any two surfaces, which was used to construct a grounded hierarchical surface categorization.

Finally, Dallaire et al. [13] have designed a 2.38 mm diameter steel stylus attached on a triple axis digital MEMS accelerometer for surface discrimination. This tactile probe was tested on a large collection of flat surfaces demonstrating surface discrimination capabilities. Temperature is a very important cue to the human perception system in order to distinguish between different type of fibers, their thermal properties could be a good discrimination factor [25]. Temperatures of objects without any heat source do not vary among each other, but heat flow to the object depends on the materials and can be used for recognition [64].

In this sense, Castelli [8] illustrates a compact device composed of a capacitive tactile sensor and a thermal sensor. The tactile sensor constitutes of an 8 x 8 array of capacitive cells, and using as thermoresistors the row's traces of the matrix of the capacitive tactile array, thermal gradient of the temperature is detected.

Engel et al. [17] present a multimodal sensor that can detect hardness, thermal conductivity temperature and surface contour of a contact object. The sensor consist of an array of sensor nodes, each composed of four distinct sensors: a reference nickel resistance temperature device (RTD) for temperature measurement and compensation, a gold heater and nickel RTD pair for thermal conductivity measurement, a membrane with a nickel-chrome alloy (NiCr, 80:20 wt.) strain-gauge for contact force and hardness sensing, and a NiCr strain gauge reference contact force and hardness sensor.

A multimodal sensitive system is described by Stiehl and Breazeal [62]; for their multi-modal skin they use 3 different sensors: force information is sensed using Peratech Quantum Tunneling Composite sensor (QTC), temperature is sensed through the use of thermometrics NTC thermistors and in order to measure the proximity of a human hand and distinguish it from the contact with an object, an electric field sensor is used. In the design of the sensor there is a problem related to the fact that the silicone used in the skin is a thermal insulator, thus the thermistor must poke through holes in the silicone skin in order to be an effective sensor. This leads to problems related to longevity of the sensor; a possible solution presented is to use thermally conductive silicones.

Takamuku et al. [64] have designed a soft anthropomorphic finger with thermal and tactile sensing elements embedded in soft polyurethane material. The sensor has been developed by embedding miniature thermistors into the anthropomorphic fingertip and also a heat source to make difference in temperature between the object and the robot hand.

A heat flow sensing device for material discrimination is used by Katoh et al. 2009 [27]. The device is made by a structure of three layer separated by PDMS spacer and consists of a micro heater and two resistance-temperature detectors (RTD). Temperature gradient induced by heat flow, differs among materials of contact objects.

Lin et al. [37] have developed a finger-shaped sensor array that provides information about the contact forces, microvibrations and thermal fluxes induced by contact with external objects. Thermal energy from the embedded electronics is used to heat the finger above ambient temperature, similar to the biological finger. This enables the material properties of contacted objects to be inferred from thermal transients measured by a thermistor in the sensor array.

A different approach is presented in Sato et al. 2011 [55] where a vision-based thermal sensor utilizing thermo-sensitive paint and a CCD camera for telexistence is proposed. The thermo-sensitive paint is employed to measure thermal information on the basis of its colour, which changes according to its temperature. Temperatures in the range of $1545°C$ can be measured. However the conventional prototype has problems, such as the measurement range and time response. This could be avoided choosing the appropriate thermo-sensitive paint and elastic material to accurately simulate the thermal interaction between an object and the human fingertip. Mechanical properties of materials, and in particular softness, can help to distinguish between textiles; Omata et al. [50] propose a tactile sensor specifically designed for detecting tissue characteristics, in real time. To do this, a combination of a piezoelectric transducer and a pressure sensor element is used. The tactile sensor system presented is able to discriminate between hardness and softness of a wide range of test objects. The PZT transducer is excited to vibrate at its inherent resonance and the mechanical characteristic of the object is determined due to the change of its vibration during contact.

2.3 Dual arm manipulation

Dual-arm manipulation has been an established technology at the beginning of the *CloPeMa* project. The aim is to implement the state-of-the-art methods on the *CloPeMa* dual-arm robotic system, which is going to be based on standard industrial robots and their controllers.

Multi-robot and cooperative systems began to be of interest to theoretical mechanicians and roboticists in the 1970's. Collision avoidance and planning robot hand trajectories for dual robots, whose workspaces overlap, is an enabling technology for *CloPeMa*. Dual-arm cooperation started in the telerobotics area. NASA reported in 1994 [3] a computer program that implements a unified control scheme for two manipulator arms cooperating in a task in which they both grasp the same object. This functionality is made available to a higher-level task-planning module. An early paper [59] already uses an algebraic approach which we intend to use as well. An early work on dual-arm robot handling a thin sheet of metal is reported in [34]. The dual-arm control for the space applications dealing with floating objects [21] is relevant too. A compliant dual-arm control method and accompanying C++ embedded DA-RL implementation has been published recently [63]. A method for trajectory generation in handling clothes is proposed in [49].

CVUT team has an experience in complicated control and planning for closed kinematic chain mechanisms [68], [70].

An interesting control package for advanced robotics named OSCAR being developed at the University of Texas at Austin. Dual-arm control is also used in industry, e.g., the welding solution using FANUC robots for Schneider Electric.

Path planning for the dual-arm robot has attracted attention too, e.g., [36]. The stress to dynamics in planning was given in [31]. In autonomous bimanual operation of a robot, parallelized planning and execution of a task is needed. Elements of a task have different functional and spatial relationships which may depend on each other and have to be executed in a specific order or they may be independent and their order can be determined freely. Consequently, individual actions can be planned and executed in parallel or not. Paper [77] shows that the structure of a task and its mapping onto subordinate planners can significantly influence planning speed and task execution.

It is also important to determine where to grasp flexible objects. The contact sensing of a compliant hand is tackled in [15]. The cloth grasp point detection is described in [40]. Manipulation based on estimated contact points is dealt with in [38].

The pair of industrial robots used as a dual-arm system needs middleware to make an interface between robot hardware and attached sensors on one side and the computational control on the other side. Probably the most used middleware is the open source ROS (Robotic Operating System). There are alternatives too, as e.g., middleware RSB (Robotic Service Bus) by the University of Bielefeld [73].

2.4 Vision for fabric identification and handling

Prior research in vision for textile manipulation has proposed that prior to manipulating and folding clothing, it is possible to identify and recognize the current observed state of fabric by extracting a number of visual cues. Key research papers included the work by Berkeley group on the PR2 robot [41] which was capable of skillfully handling and folding towels. This robot's vision system consisted of combined high and low-resolution stereo-pair cameras from which dense (low-resolution) optical flow for spatio-temporal continuity could be computed by tracking feature locations, corner detection from (high-resolution) 3-dimensional geometric models and simple "green screening" for cloth segmentation. Clothing manipulation vision systems have also employed trinocular camera configurations [28] to extract a 3D model of the cloth in order to reason and plan based on the current state of the cloth. That is, reasoning consisted in simulating the dynamic motion of clothes in order to find potential grasp points and, consequently, plan the sequence for folding clothing.

Alternative feature extraction techniques have been created to serve the specific needs of clothing manipulation. For example, wrinkle features [75] have been proposed based on training an SVM using intensity histograms extracted from images filtered by a bank of 20 Gabor filters. This was employed to learn the appearance of manually-identified examples of clothes. Graph cut segmentation is subsequently applied to the output of the filter banks in order to group and isolate the identified clothing.

Recently, scientists have realised that active sensing improves the overall task of handling and identification [11, 29, 46, 44, 74] in order to recognize the currently observed state of the garment. The active sensing task includes the identification of visual cues for grasp points, depth measurements, garment isolation and classification of contour shape when items of clothing are lifted, suspended and manipulated. The most representative state-of-the-art papers in 3D and 2D visual techniques are described below.

The current version of Berkeley's PR2 robot is the most visually competent robot for cloth manipulation [11, 46, 44]. Recently reported work includes [44] where the authors employ a quasi-static cloth model in order to avoid the need for complex dynamic representations of clothing shapes. These quasi-static cloth models are represented in terms of contour landmarks that are triangulated as simple geometric primitives (i.e. polygons). Corner detection is performed by finding edge discontinuities in 3D and extrapolating these edge positions to find intersections at a corner. From these geometric primitives, the robot is therefore able to reason and create a motion plan for carrying out garment manipulation and consequently visually tracking the folds to supervise the folding sequence.

Similarly, in [46], the Berkeley PR2 robot has also adopted these simple primitives to create parametrized shape models for each clothing category; namely, *towels, trousers, short-sleeved shirts, and long-sleeved shirts* [44]. These models describe an arbitrarily complex representation in terms of a simple low-dimensional parametric model. Each category therefore consists of a set of shape parameters that are subsequently employed to find the best fit from the currently observed garment state and, therefore, to perform deliberative manipulation of the garment. Additionally, these primitives have been used together with a Hidden Markov model (HMM) [11] to estimate the identity and track the garment's configuration from a *"non-desired"* to a *"desired"* configuration (i.e. from a crumpled state to a flattened-out state) before any planning of the folding sequence is carried out.

Active sensing has also been termed as *"interactive perception"* [74] and *"informative vision"* [29]. For example, the robot described in [74] is able to extract and classify garments sequentially by means of: a) a graph cut segmentation algorithm to isolate the garment from a pile and a stereo matching-based technique to determine the grasping point; and, b) simple image segmentation techniques for categorization of garment class (e.g. binary silhouettes and canny edge detector), respectively. By employing pure visual information (i.e. vision is the only sensing source in this robot), the robot is able to extract successfully an individual garment from a pile of garments based on a closed-loop verify-grasp cycle (i.e. the robot attempts to grasp and then verifies that the garment has been picked up; if the robot fails when grasping the garment, the process is repeated until the garment is picked up) and then classify it according to four different clothes categories (as in [44]). Similarly, Kita et al. [29] propose a strategy based on robot-state actions as the core driver for observing a garment "informatively". Each observation is employed to simulate the 3-dimensional dynamics of the cloth in order to create a manipulation and folding plan. They employ full resolution dense range maps to extract and then recognize the type of garment by finding the best 3-dimensional representation stored in a database.

2.5 Cognition in handling and understanding clothes

Home service robots face a lot of tasks concerning the handling of clothes. In particular, the task that has received most attention in the literature is robotic laundry handling. This complex task may be subdivided into four subtasks, a) isolating one piece of cloth from a washed mass, b) recognition of the type of garment that is isolated or classification into a known category (e.g. pants, skirt, t-shirt, towel), c) bringing a piece of cloth into a desired configuration so that it is spread without folds and wrinkles, i.e. unfolding, and d) folding. Although the above subtasks may not be always distinct or present, they provide a neat conceptual break down of the original problem. In the following, we review the literature concerning these tasks.

2.5.1 Isolation Task

The goal of the isolating task is to manage to grasp only one piece of cloth from a pile of clothes and hold it in the air, with the least possible disruption of the other clothes in the pile. One approach is to find the highest point of the pile [33], or the highest region [42, 74] (using stereo-derived point cloud) and then define as grasping point the geometric center of the region (the point whose distance to the region boundary is maximum) [74]. Another approach is the segmentation of the pile of clothes into regions according to their colour or, in cases of solid colour masses, by using the shadows produced on clothes using multidirectional light [22]. In this approach the middle of the largest region is decided as the grasping point.

2.5.2 Recognition Task

The recognition or classification of a garment into a garment category, such as trousers, T-shirt, towel or skirt, when it is in a random configuration is a rather difficult task. The most common approach in the literature is an interactive perception of the garment. This means that the garment is grasped sequentially from different locations, until enough information is available to allow garment classification. Usually, this task is combined with the unfolding task in closed feedback loop.

Common approaches employ at least one or two robotic arms, gravity, working tables, machine vision and interaction with the clothes in order to facilitate their classification. Gravity is used to reduce the configuration space. For example, for a known garment type, there are only a few possible configurations when the garment is grasped by two points and left to hang freely. Similarly, using a working table, one may simulate the gravity forces and help the garment to retain its configurations when the robotic arms have to change grasping points.

Interactive garment manipulation may be thought as a sequence of elementary manipulation actions. In all the manipulations that will be described, the garment in its initial state is considered to be grasped by one point, hanging in the air. Such elementary manipulation tasks are: a) grasping a corner, b) grasping an edge, c) rotating the garment, d) dropping and repicking.

Grasping a corner of the garment is the most commonly used manipulation action. This can be the lowest corner visible when the garment is grasped by a point and left to hang freely. Alternatively, it may be the corner at the bottom of an edge emanating from the original grasp point. Alternating grasping the garment from the lowest corner, leads to a configuration which is known a-priori for each type of garment. For example in the case of a towel the final configuration is the towel grasped by two not opposite corners.

Rotating the garment around the vertical (gravity) axis, while grasping from a point, has the effect of revealing garment features, such as edges or corners, that are not visible to the observer and provides a better knowledge of its configuration. In another similar approach, the robot re-grasps edges of the piece of cloth, but even then, when the algorithm fails to detect edges, the robot grasps as an alternative the lowest point of the garment. Another way of interaction with the clothes, in order to recognize them, is by dropping and re-picking them from a random point [74]. In this way the multiple pictures of the various configurations of the article can lead to safer classification than in the case where only one picture of one configuration is taken.

Machine vision is applied to detect important features that indicate the shape of the garment, such as 2D contour, folds, corners and edges. These features are subsequently used for garment classification.

As mentioned above, the unfolding and the classification task are quite dependent with each other. Some unfolding is necessary to reveal features that will help classification and classification can be used to facilitate unfolding. This is quite obvious in the scientific literature. For example, Osawa et al [52] use the re-grasping the lowest point movements to bring a piece of clothing into a known configuration. In order to avoid mistakes in classification apart from the final configuration, intermediate configurations of the garment spreading are used too. All these instances of the article are compared with already existing templates so as to achieve a correct classification. If, in the final configuration the garment is folded in half, it is placed on a working table and, since its shape is now known, it is unfolded with a simple unfolding movement. A similar approach is used by Kaneko [26] who re-grasps the hemlines of clothes. The hemlines are detected using the shadows that appear on the garment and the convexity of its outline. The drawback of this approach is that it is used for clothes with big differences in their shape such as towels, long sleeved shirts and pants. Cosumano-Towner [10] also use the re-grasping the lowest point manipulation and employ a Hidden Markov Model for garment classification. The shape of contour of the garment when held by both hands and its height when held by one hand are used as measurements in order to compare it with predicted contours created by a simulator. These are fed to the HMM to obtained garment state and class.

2.5.3 Unfolding Task

This task may be defined as follows; Given the type of garment either a-priori or via the recognition phase, and an original configuration the goal is to bring the garment into a desired configuration. For example, in the case of a towel that is originally grasped from two opposite corners the goal is to grasp it from two non-opposite corners. For a shirt originally grasped by the sleeves corners the goal is to grasp it from the elbow corners. For formally one may view this task as re-configuring the garment by applying a set of manipulations to bring in registration with a desired configuration or template.

Maitin-Shepard [42] used depth discontinuities and sharpness of curvature to detect two adjacent corners of a towel. The robot rotates the towel until a corner is found, grasps the corner with the other hand, releases the first grasping point and repeats the procedure, excluding the lowest corner so that in the final configuration two adjacent corners are grasped. In an industrial implementation [33] uses two robotic manipulators and a slider, in order to grasp two neighbor corners of a towel. The lowest grasping point manipulation, which in the case of the towel is one of its corners, is used again. The first time the robot grasps the first corner and hangs the towel to the slider. Using two more times the lowest grasping point policy the other two neighbor corners are found. Bersch [5] transforms a T-shirt equipped with fiducial markers from a random configuration into a folded state. To finish with the unfolding procedure the robot should hold the T-shirt by its shoulders. The folds are detected from the shadow lines created on the T-shirt and the grasping points are detected with the help of cloud representation and fiducial markers. At each step of the algorithm, the configuration of the T-shirt can be calculated with good precision and a greedy policy is used for the choice of the next grasping point. Nevertheless, the average time for the completion of the task is 19 minutes. Kita et al. [30] use a mass-spring model to simulate how clothing, in particular, a T-shirt, will hang. The T-shirt is a priori grasped from a point on its hemline. Their work shows the ability of the simulator's models to be aligned with the silhouettes of the true hanging garment extracting the configuration of the clothing article with a good success rate. In addition their system is able to identify and grasp a desired point with the other gripper. Cosumano-Towner [10], also consider a reconfiguration phase, after the implementation of the lowest hanging point technique and the classification of the garment under study, which lies on a working table. In this phase, the goal is to bring the article into a desired configuration (e.g. grasp the T-shirt from its shoulders) by following a planned sequence of two points re-grasps and lay-downs. An a priori known graspability graph, which indicates which other grasps states can be reached from each grasp state, is used for this procedure. Another approach presented by Salleh [54] for the detection of two corners of a towel is edge tracing by inchworm robot grippers. The edge of the towel is traced through feedback provided by infrared sensors mounted on the grippers.

2.5.4 Folding Task

After the recognition and the unfolding of clothes the folding task follows. Osawa [51] developed a robot capable of using a “flip-fold” for folding and a plate for straightening out wrinkles. The work of Maitin-Shepard [42] deals specifically with folding towels. This work focuses on visual detection of the vertices of the towel, and uses a scripted motion to achieve folds. Miller et al. [45] uses a geometric approach to robotic laundry folding. They present an algorithm that, given the geometry of the garment, computes how many grippers are needed and what the motion of these grippers are to achieve a final configuration specified as a sequence of folds.

3 Discussion of the relevant state of the art

3.1 Hands & grippers, sensors

The main tasks of the robot hand (or gripper) are picking and understanding the clothes. So we need two types of grip mentioned in section 2.2.1. Power grip will be performed by the palm and supporting finger(s) for holding, while the other two fingers (thumb and index) will explore the attributes of the cloth. The total number of fingers could be 3 or 4 because we need 2 fingers for the classification task.

To be more specific, the thumb and index finger will form the subterminal pinch in which we will have space (at the distal phalange) to integrate sensors. The movement of fingers will be under-actuated with tendons force transmission. The finger joints will be made in rubber or multilayered flexible material. About the applied griping force, the initial one could be referenced form the state of the art. Other griping experiment will be helpful in defining the appropriate values.

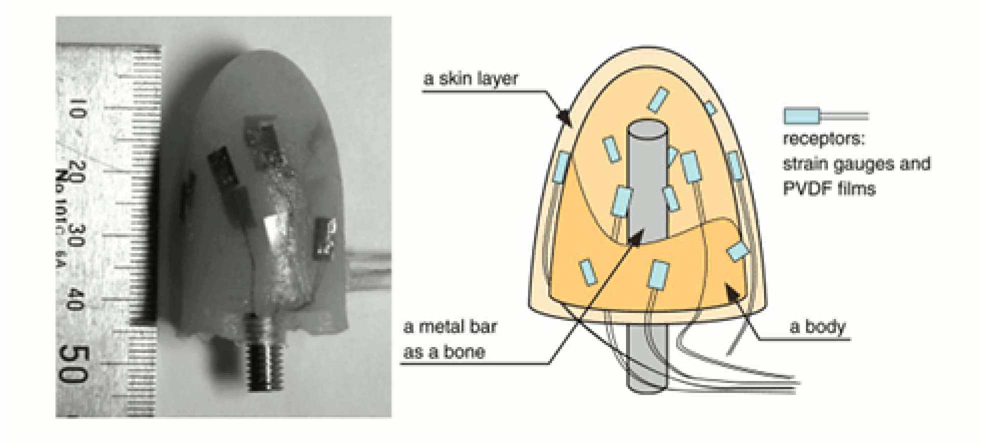


Figure 12: A developed fingertip (*left*) and its cross sectional sketch (*right*): The fingertip consists of a metal bar, a body, and a skin layer inspired by the structure of the human finger. The body and the skin layer are made of different kinds of silicon rubber. Strain gauges and PVDF films are embedded randomly in the body and the skin layer as receptors.

After picking the clothes, some other exploration procedures will be needed to understand the properties of the clothes such as, material, roughness, etc. These include static contact, lateral motion and pressure as in fig.8.

From the state of the art on tactile sensors it should emerges that the process of extracting features from fabrics during manipulation is a quite novel and on going activity. Until now, there are no specific guidelines to follow for building a reliable and application independent device able to classify and manipulate different garments. Instead, a number of transduction mechanism for measuring physical quantity such as thermal dispersion [8, 64, 27, 37, 62, 17], stiffness or strain[12], have been presented but they cannot be regarded as a definitive and comprehensive solution and there is no evidence that they can be easily integrated in a common platform. For these reasons, the sensor development strategy that will be adopted in CloPeMa is organized as follows: (*i*) selection of the relevant features to extract from garments, (*ii*) the sensors design and (*iii*) integration. Therefore, the research activity can be divided in two main parallel tasks. The former consists in the design and extensive experimental validation of tactile sensors exploiting the most promising available techniques for extracting features from fabrics. The latter will continue the bibliography research extending the scope to research areas affine but not limited to garments classification. These two tasks will be performed in a synergic fashion. New methodologies found in literature will be inserted in the developing and testing process while the experimental results can lead to new directions in the research activity. Within this deliverable, the most promising transduction mechanism, suited for garments classification, will be individuated and will serve as the starting point for the selection of the final device sensing modalities. It must be pointed out that this is a provisional choice that can be modified or integrated during the early stages of the project.

Part of the research activity in robotics has been devoted to the design and develop-

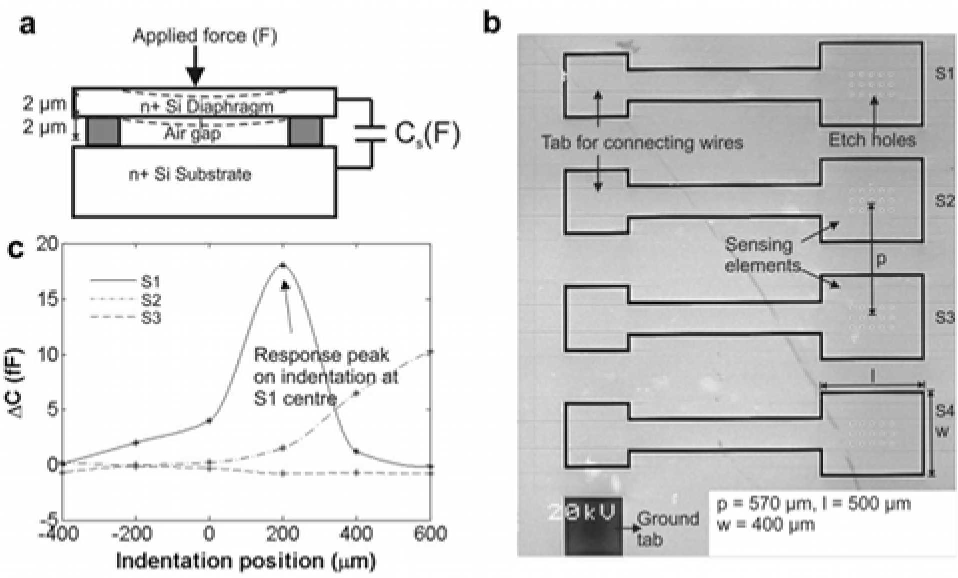


Figure 13: (a) Schematic of cross sections of single sensor, (b) SEM image of 1 x 4 linear tactile sensor array showing geometrical dimensions of device, and (c) Response of sensors in an array to spatially varying stimuli.

ment of tactile sensors for covering grippers or human-like robotic hands. The importance of having a sensitive interface for manipulating objects, has stimulated the researchers to investigate a number of different transduction mechanisms for characterizing physical interactions. Although not specifically designed for manipulating and perceiving clothes, a number of devices can be found in literature that can measure, e.g., normal and tangential forces[12]. However, most of them do not go beyond the experimental stage and very few examples can be reported about long-lasting tactile sensors successfully operating on a robotic platform or employed in an industrial application. In CloPeMa, the research activity on tactile sensors involved only in the manipulation task will be focused on the engineering of the state-of-the-art devices, rather than investigating new transduction principles with the purpose of designing a reliable and market-ready device. In the last few years, a number of review articles on tactile sensing have been presented [72, 35, 12] facilitating the selection process of the most suitable technology for clothes manipulation. According to [12], tactile sensors based on capacitive transducers are sensitive, can be easily produced and integrated on a robotic platform [57]. A high spatial resolution can be achieved by adopting MEMS based sensors as presented in [47, 48]. In addition, a number of commercial devices are already available in the market. In [47, 48], capacitive sensors were also used to distinguish two different kind of fabrics proving that the transduction principle can be used both for manipulating and perceiving clothes. Moreover, by purposively controlling the gripper and merging the information of position and velocity with the data acquired by tactile sensors, it is possible to obtain further properties of objects, such as roughness and stiffness.

Regarding clothes classification, just a few examples can be reported where tactile

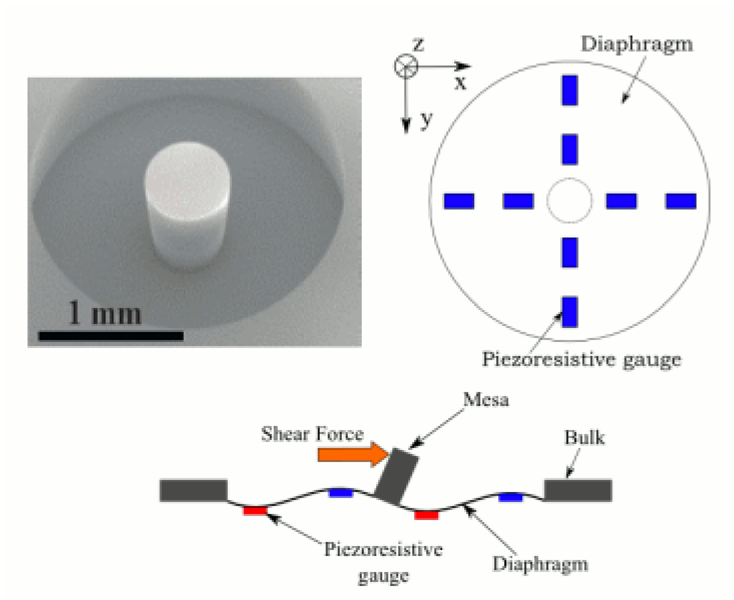


Figure 14: Three-axial sensor made in a silicon mono-crystal. Top, Left: Scanning Electronic Microscopy (SEM) photo of the three-axial sensor. Top, Right: bottom view of the diaphragm. Bottom: Diaphragm deflection when a force is applied. Here, red gauges are stretched by the deflection, blue gauges are compressed.

sensors have been mainly used for detecting the texture of fabrics or different materials [47, 48, 6, 61]. In these works, it is shown how different textures induce different intensities of vibrations and consequently, textures can be distinguished by the presence of different frequency responses of the sensors. However, none of these examples appears to be dominant with respect to the others and the use of different kind of classification algorithm prevents to compare the techniques from the experimental results. The selection process must be conducted carefully. Up to now, we can only individuate the technologies that will be analysed and compared using a common testing platform. In [6] a 3-axial force MEMS based on piezoresistive gauges is used to discriminate periodic or random coarse textures from fabrics or papers. In [47, 48], capacitive MEMS based sensors where used to distinguish polycotton from nylon fabrics. The work presented in [23] and [24] shows that transducers made by PVDF films embedded in a silicone finger are really sensitive to mechanical vibrations, induced by the pattern of different materials such as vinyl, wood and sponge. A different approach could involve three-axis accelerometers installed on a ABS fingernail as presented in [61], where, by scratching the surface, the robot was able to classify up to 20 different materials.

Measuring the thermal dispersion of a fabric can be a good parameter for classifying clothes. In fact, the composition of a fabric is in part designed for obtaining a desired heat transfer between the human body and the environment. Except for the singular work presented in [55], other techniques [8, 64, 27, 37, 62, 17] are based on a heating device plus a temperature sensitive element, such as thermistor or resistance temperature detectors (RTD) for measuring the thermal flux between the probing element and the touched material.

Objective	Sensor Technology
Clothes manipulation	Capacitive
Texture detection and Mechanical Parameters extraction	PVDF, Capacitive, Accelerometers and Piezoresistive
Thermal dispersion measurements	Heating device plus a thermistor or RTD

Table 3: Preliminary selection of sensors for clothes perception and manipulation

3.2 Dual arm manipulation

The dual arm manipulation is the enabling technology for the *CloPeMa* project as was said already in section 2.3. Neither CVUT nor NEO has experience with dual arm robots and related manipulation. However, CVUT team has an experience in complicated control and planning for closed kinematic chain mechanisms. NEO has implemented several (single arm) robotic systems in industry, mainly automotive.

CVUT and *CloPeMa* indirectly has to catch up the state of the art in the dual arm manipulation. The prerequisite is the collision avoidance. It is likely that part of the low-level collision avoidance will be solved by the control system of dual arm robot system. The lower-level collision avoidance has to be incorporated into the higher-level representation and planning modules, which remain unspecified at the time of writing this deliverable. To our knowledge, no other system manipulating with clothes has the higher-level capabilities, which we like to achieve in *CloPeMa* project.

CVUT and NEO intend to prepare functionalities of the *CloPeMa* experimental testbed (dual arm robot system) by Month 12, which will allow experimenting with perception-action cycle. This includes robots installation, equip them with standard industrial grippers (allowing to install simple tactile sensing on them later on), implementing middleware software (ROS is the most likely candidate), implement collision avoidance module and prepare software interface, through which the *CloPeMa* researchers will use the experimental testbed in their programs or connect their hardware (as range-finder, *CloPeMa* tactile hand, cameras).

3.3 Vision for fabric identification and handling

Passive vision systems have been popular in current research at the cost of high processing times (Section 1.3). However, active vision enables a divide-and-conquer strategy to be applied to visually onerous tasks. That is, image properties are extracted only as required by the current goals of the robot and reasoning/cognitive layers. Furthermore, active sensing offers the advantage of being able to gauge and control the robot actions by observing the changes of the geometric configurations of garments, arms and robot working space (something that tactile sensing does not solve). Therefore, the system can exploit feature maps in order to guide attention and track the current action/behavior of the robot. Full dynamic calibration of the stereo configuration might be required in order to maintain links between the tactile, cognitive, reasoning components of the project.

According to previously published research (Section 1.3), hard-coded perceptual methods have been proposed for the manipulation of non-deformable objects [44, 11, 74, 29]. The question is whether fully parametrised 3D models successfully represent such image properties and therefore raise the issue of which features are required for planning, handling and folding garments. Although approaches based on parametrised 3D models can produce high performance for specific garments and configurations, this comes at the price of high processing times and slow performance of the robot while carrying out clothing manipulation tasks. Therefore, we assert that encoded perceptual properties that are generic in purpose will be required in accordance to the task at hand. A combination of 2D and 2.5D image properties will be needed in order to obtain the fine structure information of the imaged garment. Space variant sensing techniques based on foveation [7, 2] will have to be implemented in order to reduce the computational complexity and direct focused attention and visual computational resources to areas that might potentially contribute to the task by representing extracted image properties within multi-resolution *foveated* pyramids.

To address the above, we propose to construct a vision engine capable of accelerated extraction of a combination of different low-level patch-based features based on intrinsic image properties such as: Gaussian derivatives, colour encoding (e.g. R-G, B-Y), contour fragments, local symmetry and texture, in order to produce a gamut of highly-discriminative feature encodings. While the vision engine will support the accelerated computation of clothing range maps (exploiting the accelerated intensity based image properties being extracted), the proposed approach to interpreting these range maps has the potential to avoid the need to interpret full 3D geometric models representing clothing and instead allow the robot to encode clothing surface appearance models by means of an *image-based representation paradigm* [71]. Accordingly, we propose to extract patch-based features representing intrinsic range image local properties, such as: surface normals, curvature, shape index and range surface Gaussian derivatives.

The above approach is intended to avoid the need to utilize 3D models to interpret the dynamic state of the garment, and instead, enable the robot to exploit reinforcement learning and learning-by-demonstration techniques (e.g in [65], the authors propose to learn by demonstration the required steps to dress a mannequin). Therefore, low-level feature descriptors will serve as visual atoms in order to create a hierarchy of visual representations that can potentially describe the state of the garment and, furthermore, other objects and working environments in the world.

Layers of the hierarchy of visual representations described above will consist of grouping and learning visual features from lower layers (by means of clustering & inference techniques) in order to create the next layer in the hierarchy. Within this framework, we propose to employ reinforcement learning to train visual texture/appearance vocabularies at the bottom layer of the above hierarchy to generate higher level features. The latter can serve as symbols, representing descriptions in terms of perceptual properties extracted at lower layers, that have diagnostic utility for tasks such as recognition, classification and segmentation. Such grouped extracted features are intended to capture the surface appearance of clothing in terms of visual components to provide a vocabulary of high-level garment concepts (e.g. “lapel” or “cuff”) suitable for cognitive manipulation.

Using the above approach we propose to combine feature extraction and segmentation in a single and unified framework that can be potentially employed for *a ”garment state recognition”* engine provided in the reasoning and deliberative modules of the project. Furthermore, within any single foveated observation of the scene, the proposed multi-modal representation will be able to support queries into the image such as “what is visually represented in the fovea” in terms of high-level symbols or low-level primitive descriptions such as colour, contour shape or texture appearance, or “what type of scene is being viewed” by considering the visual word statistics at the different levels in the grouping hierarchy over the field of view.

3.4 Cognition in handling and understanding clothes

From the review of the literature it is evident that planning is needed in several stages and for different goals. Towards garment recognition, planning has to provide a manipulation sequence that will reveal as much information as possible about the shape of the item. Similarly, for the unfolding task, the role of planning is to predict a minimal sequence of manipulation actions that will bring the item in a desired configuration. Finally, in the folding task, usually a predefined (open-loop) sequence of movements is performed for the specific type of garment, yet more complex planning is required for realistic folding tasks. In all these cases planning has to be performed under the constraints posed by the configuration of the working space and the feasibility of the movements by the manipulators.

Current works employ a rudimentary form of planning based on heuristics or exhaustive search over the configuration space. Although the current paradigm adopted is interactive perception of the garment, perception, planning and action are performed in isolation to each other. Apart from the above other limitations of the state-of-the-art are:

- Some of the works are limited to specific garment shapes (e.g. towel or a shirt) and may not generalize to other more complex garments.
- Specific manipulation routines, such as picking the lower point of a garment with one arm while holding with the other arm, require significant working space. This may not be feasible with adult-size clothing and certain types of manipulators (e.g. when the distance between two points on the clothing item can exceed the arms vertical or horizontal span). Ideally the manipulation routine should be feasible within the constraints posed by the manipulator in realistic conditions.
- Some techniques employ fiducial markers for the detection of desired grasp points. This is not practical in a realistic scenario.
- The cloth is usually modeled as being non-strechable. Also garments are modeled as 2D manifolds (i.e. as being flat). How well these assumptions approximate real world conditions has to be verified.

- Some approaches rely on capturing multiple views of the object in order to detect grasp points or other features. This introduces a significant delay. Ideally the planning algorithm should work with minimal information.
- The main challenge in performing intelligent planning is recognizing the configuration of the garment with limited vision. This stems from the huge state space of possible garment configurations. Although, simplifying assumptions can make the problem tractable, this is a largely open problem.

4 Target clothes, reference heap and reference textiles

4.1 Fabric types and properties

Fabric types and technology

Fabric is an artifact made by weaving, felting, knitting or another processing of natural or synthetic fibers. The method of production and type of used fiber determine its properties.

Fibers can have natural or synthetic origin. Natural fiber comes from plants, animals or mineral resources. The most commonly used natural fibers are cotton, wool, rayon and silk.

Silk is obtained by removing the bugs from a moth (Bombyx mori). Silk is formed from a single long fine thread. It means that silk is the only continuous fiber of non-artificial origin. All the other natural fibers should be transformed into yarn by a spinning process. There are also other species of butterflies which produce the silk that can be used industrially and even the spiders produce the thread of very similar characteristics, but without the possibility of industrial use.

Wool refers to the fibers from the fleece of lambs, sheep, Cashmere goats, Angora goats, camels, llamas, alpacas, and vicunas. Wool from sheep is the most common, the lamb's wool is shorn from sheep less than eight months old, and Merino wool is from a specific breed that yields the finest and softest sheep wool. Mohair is the wool of the Angora goat.

Rayon (viscose) is made from regenerated cellulose by extrusion through minute holes. Rayon has been invented 1889 in France like artificial silk fiber. It is a man-made fiber from natural polymers. A manufactured fiber composed of regenerated cellulose in which substituents have replaced not more than 15 percent of the hydrogens of the hydroxyl group.

Cotton is the most widely used material in the textile industry. Cotton is made from a plant of the Genus Gossypium, which yields fiber for the manufacture of durable and permanent fine papers and cellulose derivatives. The boll of the cotton plant is a capsule that bursts open when ripe, allowing the seed and attached lint (hairs) to be easily picked. The cotton fiber is removed from the seed by the ginning process. Quality depends on the length of the fiber, longer being better, and fiber lengths vary from less than one-half inch to more than two inches.

Synthetic fibers are done from synthetic made polymers or monomers. Synthetic fibers have accelerated in importance in the 70's due to their lower production costs and high durability. Today, synthetic fibers have equalized cotton in production quantities. They are used alone or mixed with natural fibers. The most commonly used synthetic fibers are polyester (pile), acrylic, polyamide (nylon), polypropylene (polyolefin), polyurethane (Lycra, elastam, spandex).

Polyester has been produced since the early 1950s, and is second in worldwide usage immediately after cotton. Polyester has high strength (although somewhat lower than nylon), excellent resiliency, and high abrasion resistance. Low absorbency allows the fiber to dry quickly.

Acrylic is a manufactured fiber derived from polyacrylonitrile. Its major properties include a soft, wool-like hand, machine washable and dryable, excellent colour retention. Solution-dyed versions have excellent resistance to sunlight and chlorine degradation.

Polyamides are formed from polymers of long-chain polyamides. Produced since 1938, they have been the first completely synthetic fiber to be developed. Known for its high strength and excellent resilience, nylon has superior abrasion resistance and high flexibility.

Polypropylene is a manufactured fiber characterized by its low weight, high strength, and abrasion resistance. Olefin is also good at transporting moisture, creating a wicking action. End-uses include active wear apparel, rope, indoor-outdoor carpets, lawn furniture, and upholstery.

Polyurethane fibers have a lot of trade names. All are manufactured like elastomeric fiber that can be stretched repeatedly more than 500% without breaking, and still recover to its original length.

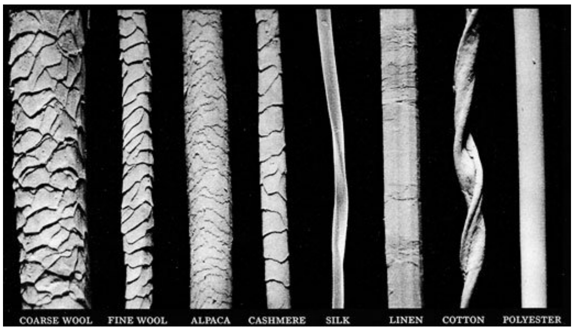


Figure 15: Microscopic view at some examples of fibers.

The textiles manufacturing process

The natural fiber mass after cleaning from impurity and parallelization of single fibers is twisted to form a continuous yarn. This process is called spinning and its product is **spun yarn**. Silk and man-made fibers have a continuous very long structure that can be used as a single yarn or twisted or only simply grouped together into a yarn called **filament**. Yarn to fabric processing is typical made by weaving, knitting or felting. The first and most important industrial method is weaving.

Weaving is a traditional orthogonal processing of yarns to produce fabric. Lengthwise yarns are called warp; crosswise yarns are called weft, or filling. Most woven fabrics are made with their outer edges finished in a manner that avoids raveling; these are called selvages. They run lengthwise, parallel to the warp yarns. The three basic weaves are plain, twill, and satin. Fancy weaves-such as pile, Jacquard, dobby, and leno-require more complicated looms or special loom attachments for their construction. The manner in which the yarns are interlaced determines the type of weave. The yarn count and number of warp and filling yarns to the square inch determine the closeness or looseness of a weave. Woven fabrics may also be varied by the proportion of warp yarns to filling yarns. Some effects are achieved by the selection of yarns or of combinations of yarns. In the plain weave each filling yarn passes over and under the warp yarns, with the order reversed in alternating rows. Fabrics made using the plain weave include percale, muslin, and taffeta. Ribbed effects in such fabrics as faille and bengaline are produced by employing heavier yarns for either the warp or the filling. In the basket weave one or more filling yarns are passed alternately over and under two or more warp yarns, as seen in monk's cloth. Twill weaves are made by interlacing the yarns in a manner producing diagonal ribs, ridges, or wales across the fabric. Wales may run from the upper right to the lower left of the fabric, or the reverse. The herringbone weave has wales running both ways. Twill fabrics include denim, gabardine, and flannel. Satin weaves have a sheen produced by exposing more warps than fillings on the right side of the fabric. The exposed warps are called floats. In the sateen weave the process is reversed, and the exposed fillings form the floats. The amount of twist in the yarns and the length of the floats produce variations. Fabrics made in these weaves include slipper satin, satin crepe, and various sateen types.

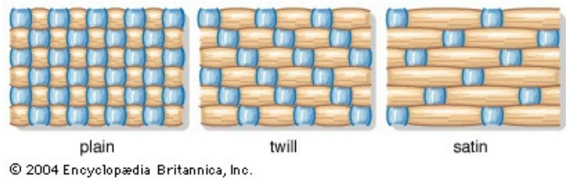


Figure 16: Three basic types of weaves fabric.

Knitted fabrics are constructed by interlocking a series of loops made from one or more yarns, with each row of loops caught into the preceding row. Loops running lengthwise are called wales, and those running crosswise are courses. Hand knitting probably originated among the nomads of the Arabian Desert about 1000 bc and spread from Egypt to Spain, France, and Italy. The invention of a frame knitting machine in is dated about 1589. The frame knitting machine allowed production of a complete row of loops at one time. The modern knitting industry, with its highly sophisticated machinery, has grown from this simple device.

Weft knitting

The type of stitch used in weft knitting affects both the appearance and properties of the knitted fabric. The basic stitches are plain, or jersey; rib; and purl. In the plain stitch, each loop is drawn through others to the same side of the fabric. In the rib stitch, loops of the same course are drawn to both sides of the fabric. The web is formed by two sets of needles, arranged opposite to each other and fed by the same thread, with each needle in one circle taking up a position between its counterparts in the other. In a 2:2 rib, two needles on one set alternate with two of the other. The interlocked structure is a variant of the rib form in which two threads are alternately knitted by the opposite needles so that interlocking occurs. In the purl stitch, loops are drawn to opposite sides of the fabric, which, on both sides, has the appearance of the back of a plain stitch fabric. Jacquard mechanisms can be attached to knitting machines, so that individual needles can be controlled for each course or for every two, and complicated patterns can be knitted. To form a tuck stitch, a completed loop is not discharged from some of the needles in each course, and loops accumulating on these needles are later discharged together. The plaited stitch is made by feeding two threads into the same hook, so that one thread shows on the one side of the fabric and the other on the opposite side. A float stitch is produced by missing interlooping over a series of needles so that the thread floats over a few loops in each course.

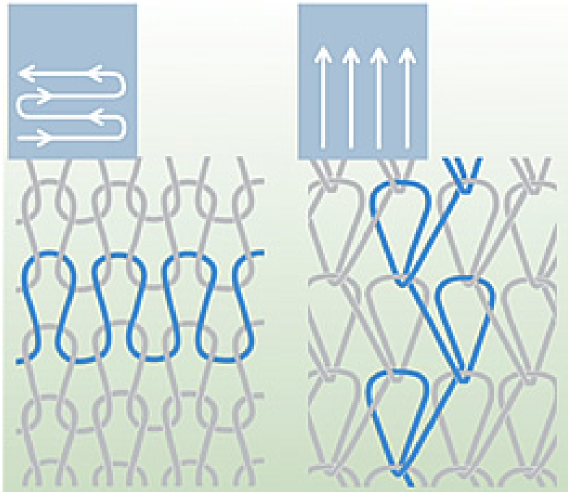


Figure 17: Weft and warp basic types of knit fabric.

Warp knitting

The two types of warp knitting are raschel, made with latch needles, and tricot, using bearded needles.

Raschel

Coarser yarns are generally used for raschel knitting, and there has recently been interest in knitting staple yarns on these machines. In the Raschel machine, the needles move in a ground steel plate, called the trick plate. The top of this plate, the verge, defines the level of the completed loops on the needle shank. The loops are prevented from moving upward when the needle rises by the downward pull of the fabric and the sinkers between the needles. Guide bars feed the yarn to the needles. In a knitting cycle, the needles start at the lowest point, when the preceding loop has just been cast off, and the new loop joins the needle hook to the fabric. The needles rise, while the new loop opens the latches and ends up on the shank below the latch. The guide bars then swing through the needles, and the front bar moves one needle space sideways. When the guide bar swings back to the front of the machine, the front bar has laid the thread on the hooks. The needles fall, the earlier loops close the latch to trap the new loops, and the old loops are cast off. Raschels, made in a variety of forms, are usually more open in construction and coarser in texture than are other warp knits.

Tricot

Tricot, a warp knit made with two sets of threads, is characterized by fine ribs running vertically on the fabric face and horizontally on its back. The tricot knitting machine makes light fabrics, weighing less than four ounces per square yard. Its development was stimulated by the invention of the so-called FNF compound needle, a sturdy device that later fell into disuse but that made possible improved production speeds. Although approximately half of the tricot machines in current use make plain fabrics on two guide bars, there is increasing interest in pattern knitting. In this type of knitting, the warp-knitting cycle requires close control on the lateral bar motion, achieved by control chains made of chunky metal links. Special effects in warp knits The scope of warp knitting has been extended by the development of procedures for laying in nonknitted threads for colour, density, and texture effects (or inlaying), although such threads may also be an essential part of the structure. For example, in the form called "zigzagging across several pillars", the ground of most raschel fabrics, the front bar makes crochet chains, or "pillars", which are connected by zigzag inlays.

An extension of conventional warp knitting is the Co-We-Nit warp-knitting machine, producing fabrics with the properties of both woven and knitted fabrics. The machines need have only two warp-forming warps and provision for up to eight interlooped warp threads between each chain of loops. These warp threads are interlaced with a quasiweft, forming a fabric resembling woven cloth on one side.

Felt fabric

Felts are a class of fabrics or fibrous structures obtained through the interlocking of wool, fur, or some hair fibres under conditions of heat, moisture, and pressure. Other fibres can be mixed with wool, which acts as a carrier. Three separate industries manufacture goods through the use of these properties. The goods produced are wool felt, in rolls and sheets; hats, both fur and wool; and woven felts, ranging from thin billiard tablecloths to heavy industrial fabrics used for dewatering in the manufacture of paper. Felts of the nonwoven class are considered to be the first textile goods produced, and many references may be found to felts and their uses in the histories of ancient civilizations. The nomadic tribes of north central Asia still produce felts for clothing and shelter, utilizing the primitive methods handed down from antiquity.

Physical and mechanical properties of fabric

In the above classification of fabric we simply described the production method and materials used, which determine its geometrical and material structure. So we can presume the fabric properties based on statistical knowledge of similar materials. One example of descriptions can be the following in (fig. 18)

For quality management feedback, new material development or unknown materials, simple laboratory experiments are employed. The laboratory exam based on samples, usually starts with examination of microscopy photos of the structure of fabric, and it relies to technician's experience for recognizing the structure and classify it according to the production technology. In the same way the technician detects visually the type of used fibers. In case of multi-layer or very complicated fabric structures it is necessary to disintegrate a piece of fabric wire by wire to understand its composition. Following tests

Union fabrics	Direction	Fiber content	Yarn type	Twist direction	Yarn count	Threads per inch	Cover factor	Cloth cover	Weave type
Viscose rayon x Viscose	Warp	Viscose rayon	Single	Z	75d	101	12.65	17.12	Plain
rayon (control, (VR)	Weft	Viscose rayon	Single	Z	75d	83	9.98		
Viscosesrayon x Eri silk	Warp	Viscose rayon	Single	Z	75d	101	12.78	21.25	Plain
of $2/40^S$ (VRE_1)	Weft	Eri silk	2 ply	S	$2/40^S$	51	15.60		
Viscose rayon x Eri silk	Warp	Viscose rayon	Single	Z	75d	101	12.28	19.96	Plain
of $2/60^S$ (VRE_2)	Weft	Eri silk	2 ply	S	$2/60^S$	58	13.99		
Viscose rayon x Eri silk	Warp	Viscose rayon	Single	Z	75d	101	12.18	20.09	Plain
of $2/80^S$ (VRE_3)	Weft	Eri silk	2 ply	S	$2/80^S$	72	13.80		

Figure 18: Constructional details of Viscose rayon and silk union fabrics.

with use of special test bed destroy the sample piece of fabric to measure its physical and mechanical properties, possible durability problems and non-aesthetic aspect. Results of this exam add to previous description the following data. Real yarn count (could be different in comparison with designed ones due the production imperfections), specific gravity, fabric thickness, fabric stiffness, tensile strength elongation, abrasion cycles resistance, drapability, pilling resistance, perforate resistance.

Some of this properties can be measured in non-destructive way while others cannot. *CloPeMa* hand should be able to take perception of material characteristic only by touching, pulping of sliding on fabric surface. The tactile sensors are able to measure roughness that is related with texture (type of weaving or knitting), yarn or stitch count, cover factor and used fiber type of fabric and its properties. The measurement of thermal dispersion is a new approach to distinguish the fabric material composition. The thermal dispersion of fabric depends on its thickness, thermal properties of used fibers and their planar density.

4.2 Typical laundry heap

The typical laundry heap is about 14-15 pieces (of man and woman garments) for the 5kg-6kg washing machine, noticing that the weight of the laundry heap could be less than the capability of the machine depended on the volume of the laundry heap.

Type of usual worn garments and their price range

To define what type of clothes we usually have in our closets, we took reference data based on the online shop www.amazon.fr (collected in 03/2012). It is assumed that the number of articles in each clothe category reflects the popularity of that one.

In fig.19, fig.20, fig.21[2], the kind of garment as well as the distributions of them in each range of price are shown. For example: in the case of woman tops, most of the products are in the range of 20-39.99 Euros.

Typical laundry heap

We focused on the casual wear because that is the clothes we wear the most. Considering the popularity of the type of clothes and the number of articles in different price ranges,

[2]The prices of hoodie are depended on the size that why the sum of all the price ranges is larger than the total number.

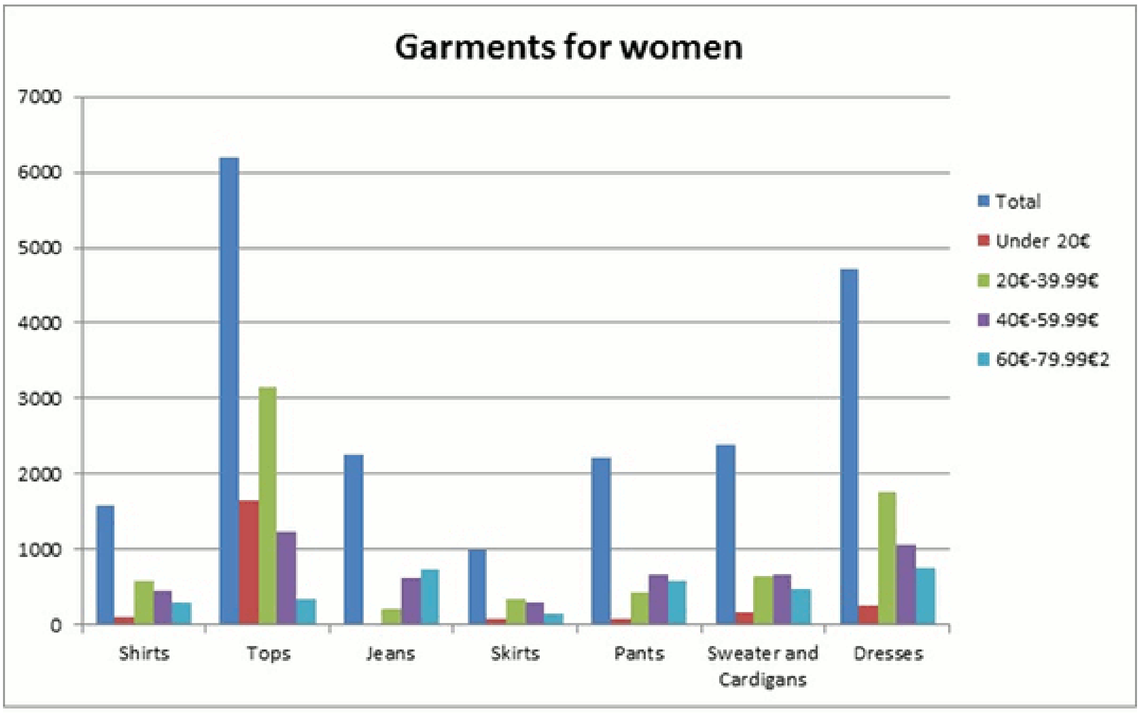


Figure 19: Garments for women

the price 20-40 Euros for tops (shirt, t-shirt, sweaters) and up to 40-60 Euros for pants (jeans, trousers, etc.) are suggested.

The laundry heap that would be proposed includes all the clothes that men and women usually wear (all the categories in previous section) are listed in the table below.

Women	Man
Shirt	Shirt
Top	Jean
Jean	Pants
Skirt	T-shirt
Pants	Sweater
Sweater Cardigan	Sweater
Dress	Hoodie

Table 4: List of clothes in the laundry heap

5 Three *CloPeMa* demonstrations

The overall picture of the intended three *CloPeMa*demonstrations was given in the Description of Work, page 7, Table 1. Here, M12 scenario explicated more in detail. The M24 and M36 scenarios are only sketched because their specification will be trimmed after experience with the M12 demonstration is acquired.

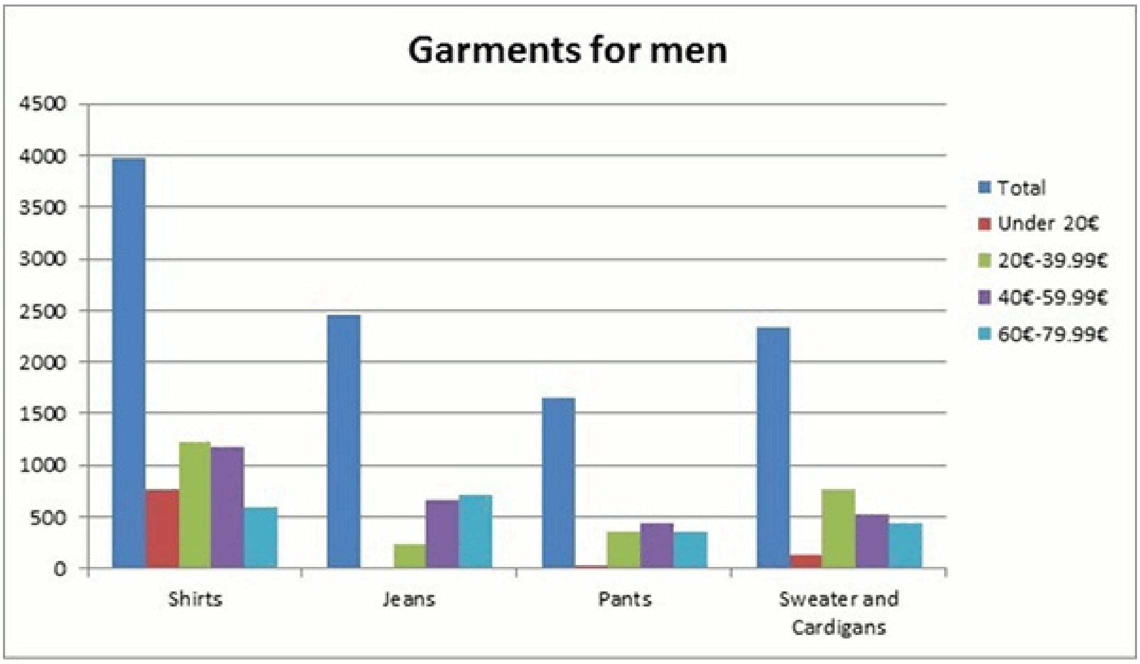


Figure 20: Garments for men

5.1 M12 scenario: targeted achievement and demonstration

- UniGe
  At the first demonstration, UniGe will have the initial prototype of a mechanical hand (gripper) that can pick a towel lying on the table and perform some exploration procedures as explained in section 3, especially the lateral motion. The gripper will not be affixed on the robot arm, but if necessary its movements will be simulated manually. The structure of the finger will be divided in three basic layers which are sensing, flexible bearing (super elastic alloy) and actuator one. The force transmission will be made by tendons actuated by variable impedance actuators embedded in forearm. The concept of three separated layers has a goal to maximize the contact surface for sensing. The towel will be picked and lifted by pair of fingers. Another finger will grasp a hanging part of towel under the grasping point and slide against the palm to perform the lateral motion for tactile sensing. The sensors will not be embedded but their performance will be demonstrated on a separate test bed. The related sensors like tactile, heat, sound, etc will be functionally presented and will provide the information about the object. The integration of the sensors to the hand could be at the basic level. During the first year an experimental setup will be built where different transduction mechanism can be tested, possibly at the same time, with different types of garments. The aim is twofold, on one side different sensors are compared in order to determine the set of features that can be extracted from fabrics and which is the best transduction principle for each feature. On the other side, the platform design and the experimental results will reveal how to integrate the sensors on the first gripper prototype.

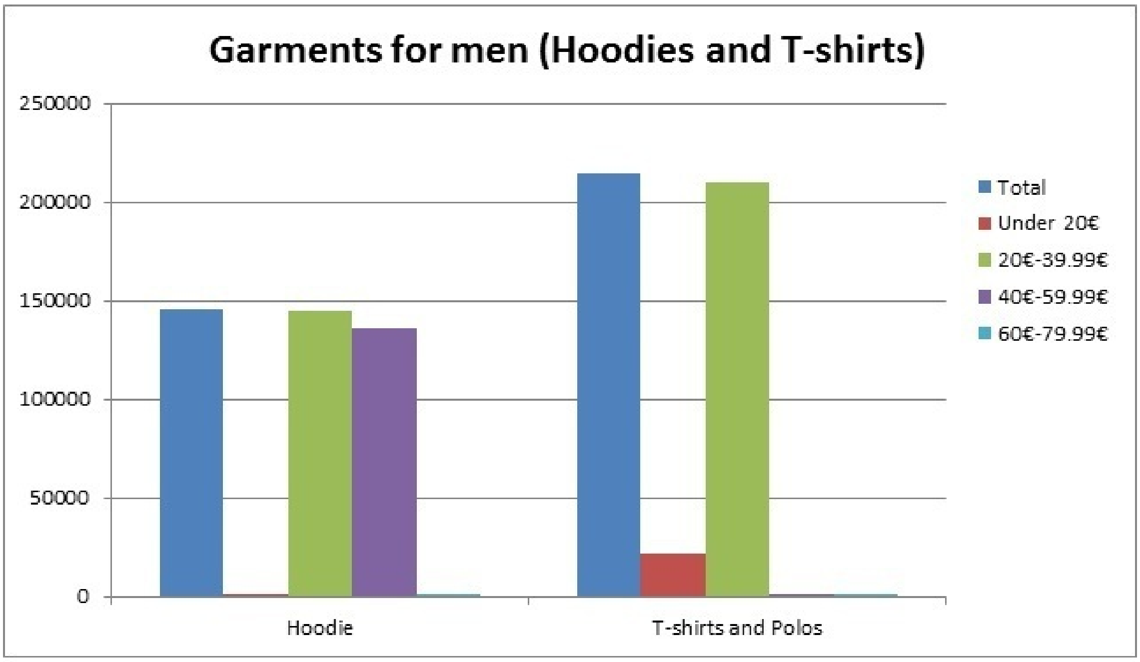


Figure 21: Garments for men (hoodie and T-shirts)

Figure 22: A 150mm long micro metric linear stage actuated by a stepper motor.

Since the experimental test bed should be available in the early stages of the project, the design will focus not on the realization of a generic gripper but on a platform where it is possible to precisely control the interaction of the fabric with the sensor under test in terms of position, velocity, acceleration and force. The test bed will be composed by a moving platform where a piece of garment can be installed and controlled in both position and orientation. The structure is completed by an additional arm required for placing different sensors over the platform and controlling the interaction with the fabric. The state of the system will be monitored thanks to a number of sensors for measuring namely, interaction forces, moments and position of the fabric with respect to the sensing element in order to be able to repeat the tests in the same conditions. The moving platform will be made by two linear motorized stages (see fig.22) with micro metric positioning capability. The motors will be arranged in order to move the platform in two orthogonal directions. The stages will be selected preferring the positioning precision and repeatability rather than motion speed. The orientation of the platform will be controlled by a motorized

Figure 23: A 360 degrees continuous rotation stage with stepper motor actuator.

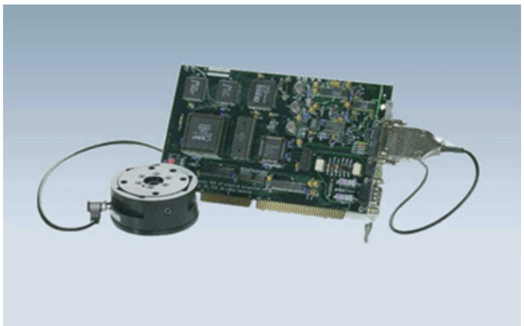


Figure 24: A 6 axis Force-Torque sensor along with the acquisition card.

rotation stage(see fig.23) mounted on top of the two linear motors. In this manner it is also possible to apply tangential forces and moments normal to the fabric's plane by moving the platform when the fabric is in contact with the sensors. The physical interaction will be measured thanks to a 6 axis force torque sensor (see fig.24) attached to the moving platform. The different transduction techniques will be tested by installing the sensors on a structure placed over the moving platform. An additional force-controlled linear motor is required for moving the sensors towards the fabric and controlling the physical interaction.

The test bed will be automated by implementing a centralized control system on a PC with a real-time operating system. Moreover, the different sensors will be interconnected using a bus, e.g., CAN or EtherCAT just to name but a few, for acquiring and synchronizing the measurements.

- CVUT
  The Czech Technical University in Prague will contribute in two ways. First, the *CloPeMa* experimental testbed will be gradually developed and used in project experiments. Second, the preparatory steps in recognition, learning and active exploration (WP6) will be conducted. CVUT team will also cooperate with CERTH and other partners on higher-level representation and reasoning (WP6). Only preliminary results are expected here.

  The Month 12 demonstration will be run at CVUT with the aim to demonstrate basic manipulation capabilities of the *CloPeMa* dual arm experimental testbed. The system will be able to locate a towel and fold it. The goal is mainly to demonstrate the manipulative abilities of the system. The degree of the involved cognitive feedback will be rather limited.

- CERTH
  During the 1st annual review meeting, CERTH will demonstrate the basic functionality of the miniature Photometric Stereo system. The lab prototype will be utilized, during the demo session, for the micro-texture three-dimensional reconstruction of various fabrics. Furthermore, a first version of the fabric recognition algorithm will be presented as a proof-of-concept, demonstrating the process of comparing certain textile types through texture differentiations.

  Also, CERTH will demonstrate preliminary results on a planning algorithm for reconfiguration and folding of a known garment. An online demo using a cloth simulator will be also provided demonstrating intelligent planning and manipulation of a towel.

- UG
  University of Glasgow will develop a binocular Robot Head comprising a stereo-pair of actuated cameras, each camera mounted on accurate pan-tilt actuators (suitable for photogrammetric measurements) and the assembly mounted on a commercial-off-the-shelf (COTS) camera mounting frame. We will integrate an illumination system, under computer control,within the vision head. An acquisition interface will be provide that supports, stereo-pair image capture, camera pan/tilt control and automatic vergence control either by physically converging or diverging the cameras or by shifting the offset between the captured stereo-pair images.

  Range capture will be supported based on the above head using the UG C3D technology integrated in ROS to provide high resolution full field-of-view (FOV) range maps. We shall investigate modifying C3D to provide range maps based on processing a small region-of-interest (ROI), for example 512x512 pixels, in order to reduce range map acquisition and processing times very substantially. Camera calibration will be provided using multiple observations of a planar target. We shall provide the templates for a family of planar targets of differing sizes, to allow these to be reproduced (by printing on photographic quality paper and mounting on a rigid plane) in different locations or contexts as required. Based on the results of our investigation into dynamic calibration, the calibration system will maintain the calibration of the camera system under extrinsic camera movement.

  SIFT feature extraction from each camera in the binocular head will be provided based on existing C codes, extended to match colour features. This version of SIFT provides fast foveated feature extraction. The SIFT features extracted from each camera of the stereo-pair will be matched to each other to form inter-camera correspondences. Therefore, range values (or world space X,Y, Z locations) will also be provided with these SIFT keypoint locations. The above facilities will be integrated within the ROS environment.

- NEO
  Neovision s.r.o. will prepare the first working version of the hardware and software

interfaces (middleware) to *CloPeMa* experimental testbed. The interfaces will allow other partners to incorporate their modules to the gradually built *CloPeMa* system.

5.2 M24 scenario, early specification

- UniGe
  The *CloPeMa* hand will be complete and fully integrated (UniGe). Its demonstration will focus on its manufacturing (construction and assembly) and on its functional characteristics and performance. The aim of this double focus is to underline the good design for manufacturing and the cost-effectiveness of the hand, in line with the purpose of proving that the *CloPeMa* technology has a close industrial impact.

  The hand production procedure will be illustrated, detailing the fabrication steps, the timing, the resources involved. The level of readiness will be indicated and proven. The results of life-cycle tests will be provided underlining the critical parts, an estimate of the MTBF, the actions for the achievement of the full readiness level (9).

  The hand will be demonstrated stand alone to highlight its performance in the execution of each single manipulation task and of the sensing performance. A set of fabric samples will be prepared with suitable arrangements. Tip pinching, palm grasping and holding, finger rubbing will be demonstrated on the set of samples. The reliability of the grasping and the forces will be assessed/measured with the same equipment used during the initial phase of handling task characterization. The dexterity of the hand will be proven through a set of experiments of manipulation in-hand of samples.

  A group of experiments will be dedicated to the sensorial parts of the hand. The capability of sensing and characterizing different textiles will be proven on a set of samples. The processing of the data, the robustness of the algorithms and the time of processing will be shown and assessed.

- CVUT
  At this step, the hand will be assembled to the robot and starts to collaborate in picking and moving motion. The control of the manipulator (CVUT) includes continuous picking points needed to be handled to perform the recognition process.

- CERTH
  The developments of the photometric stereo sensor will be concluded during this period. The initial prototype will be optimized with respect to its dimensions, resolution, accuracy, speed and classification algorithms. Integration with the *CloPeMa* hand will be also concluded as well as interfacing with other modules of the experimental testbed. CERTH will present extensive results on cloth material classification using the proposed sensor device. The sensor will be also demonstrated integrated on the platform i.e. within a perception-action cycle.

Research on cognition and planning will be demonstrated by means of a pragmatic task performed by the *CloPeMa* robot, thus demonstrating integration with the *CloPeMa* platform. The basic garment reconfiguration task will be demonstrated, using primarily vision cues on garment of moderate complexity. The tower of knowledge architecture (ToK) will be exploited to provide hypothesis for sensors and plan actions of the manipulators. CERTH will also present extensive evaluation results that justify the advantage of the proposed planning algorithms with respect to the state-of-the-art, especially regarding speed and accuracy in task execution.

- UG
  UG will demonstrate a vision system that integrates range sensing and feature extraction within a unified architecture. This architecture adopts multi-resolution foveated data structures on which high quality foveated range sensing and foveated feature extraction will be based. This will comprise a scalable generalised architecture for extracting low-level 2D & 2.5D image primitives, cues and feature descriptions. We propose to demonstrate the construction of both standard feature descriptors, multi-modal descriptors and also investigate and implement novel feature descriptors which have been tailored to meet the needs of clothing analysis.

  UG will demonstrate an accelerated (multi-threaded C++ with GPU acceleration) version of the UG matching software currently coded in Java. This task will entail implementing an accelerated base foveated pyramid architecture that combines multi-resolution matching, regularisation and range map construction functions.

5.3 M36 scenario: Industrial application scenario, the early specification

The experiments carried out at the end of the project comprise the development of an application closer to the potential industrial use of the *CloPeMa* technology. The bottleneck to the 3D assembly of products made of soft items joint together is in the loading of the items on the mould, as detailed in Section 6. The scenario proposed is that the arms pick single fabric items from a table (as they would do from the cutting table); each item is positioned on a mould equipped to hold the items; in performing the loading, the *CloPeMa* system checks that the items are properly spread, without wrinkles, and their position meets the nominal for the product to assemble. An additional task that the *CloPeMa* robot could perform, at the moment mentioned but not targeted, is the preparation of the edges for joining: in the case of sewing, the edges must be bent and mated; for bonding and welding it is sufficient to check their correct overlapping.

The complete implementation of this industrial application experiment is challenging: the demonstration of the picking and handling from the table could represent already a relevant hint to the industry related to the diffusion of advanced automation in the traditional manufacturing.

The M24 demonstration will be extended in many respects. All sensors and measurements will be integrated in the ToK. Both reconfiguration and folding of a previously unseen garment will be demonstrated. Learning and adaptation will be demonstrated on garments of moderate to high complexity. Quantitative results based on controlled experiments will be also presented.

Based on the data structures used in the multi-resolution foveated range-finder, UG proposes to demonstrate accelerated extraction of the core intrinsic image properties, such as colour space maps, Hessian gradients and texture descriptor fields and core range surface intrinsic properties, such as gradients, curvature, normals and shape index fields. Potential acceleration methods include utilisation of efficient vectorising CPU instructions, parallelisation over multiple cores/processors and GPU coding. UG proposes to extend this architecture to demonstrate saliency cues being detected and feature descriptors being extracted and their vectors being matched in the context of identifying salient locations on clothing.

CERTH, UG and CVUT shall build on the accelerated foevated vision architecture to demonstrate cognitive sensing based on specialised feature extraction, matching, learning and tracking by 'tuning' the vision system in the context of the *CloPeMa* clothing manipulation tasks.

6 Industrial application

Eco-sustainability issues call for the design and manufacturing of less mass and more energy efficient products so, in the near future, wider and wider use of limp lightweight materials will be applied not only in the textile leather sectors but also in transport and in many other industrial sectors that are vital for Europe. The human inspired robotic manipulation of thin, near 2D, limp non-homogeneous and permeable parts is very difficult. Only a few dedicated and conventional systems, with a complex and time-consuming configuration and setup process, are available. For this reason, the handling operations in these sectors today are made manually or, sometimes, by dedicated automated cells. Up to now viable robust, cost efficient, flexible robotic handling solutions are not available.

A reliable and comparatively fast robotic system for the picking, handling and positioning of soft and compliant items made of thin layers (fabrics, fibres) may:

- have a strong impact on the automation of the manufacturing of all current industrial goods involving soft materials assembled in 3D envelopes,
- enable the large scale production of goods that today are extensively hand made,
- enable an increase in the sustainable complexity of the products, making cheaper products more complex to manufacture,
- create new market in areas where today the manufacturing can be only manual.

The *CloPeMa* project cannot target a fast and complete system, but may achieve a concrete advancement over the state of the art of smart limp material handling, where the systems developed are so slow that no practical use may be considered. The easiest way to explain the task performance objective, but for a future to come, is that the robot can replace a human in the handling of soft, limp items: picking, in-hand handling, positioning, folding, spreading. This would open the widest possible application scenarios: the handling dexterity would enable the use of robots for the mass-manufacturing of complex products, and the level of understanding and self-decision would raise the flexibility and the autonomy in the development of variegated and changing processes.

The following reviews in brief the main specific industrial application areas in the industrial context of today and the close future. The two major bottlenecks in the manufacturing of products involving fabric items are the preparation of the items with the need to automatically unload and sort them from the cutting table or die cutting machine, and the preparation to the joining, performed either by sewing or by new technologies (thermal or laser welding, bonding, gluing). For several other operations, rigid automation solutions exist and are used: the use of robots with sufficiently dexterous handling abilities would increase in these cases the level of flexibility.

6.1 Cutting table unloading

In the textile, clothing, shoe and leather industries the manufacturing process starts with the automated cutting of the limp/soft material: the cutting table receives the fabric from the automated store and cuts it in the desired shapes. Cutting is performed on a stiff 2D surface by a cutting head moved e.g. by a cartesian manipulator. After cutting, the parts are picked up and transferred to the following manufacturing sections.

The items are cut in single or multiple layer, i.e. as a single ply of material spread on the surface of the table, or as several layers (also 20-50) in a mattress. In all cases, the layers lie over a cutting support made of paper of cellulose fibres, and are covered by a plastic airproof film which is required to block them on the table using vacuum. When the cutting is complete over a section of the table, the items are removed from the table either one by one or in blocks. This operation is carried out manually almost always apart in the few cases of very repetitive production in single layer. The task involves the understanding of what is items and what is scraps, the grasping of a package of items, generally including the cutting support layer and the plastic film, the separation of cutting support and plastic, the singularization of the items if multilayer and their distribution or delivery to the logistics of the plant. The items are adjacent to each other and the picking of one item may cause the disarrangement of the adjacent ones, so the use of exteroceptive vision system is recommended. These operations require a very high handling skill and they are carried out by humans. Apart the disadvantage coming from the breaking of the chain of automated operations, the humans are slow and make mistakes, and the operations are repetitive and boring.

These operations do not require dual-arm manipulation and do not need finger handling. Single arms or high-speed manipulators with parallel architecture, typical of several sectors of the manufacturing and packaging of goods, may be profitably applied. The grasping of the items can be performed in principle using a vacuum device (cup, coanda) or other adhesion principles (electrostatics, chemical bonding, freezing). This may work for single layer but it is not reliable with multi-layer because more than one item at a time may be picked. A combination of grasping using one of the listed adhesion methods, followed by a check of the number of layers grasped and singularization using fingers and handling dexterity in case of more items could represent a solution of automation. The *CloPeMa* results would not be used as they are but some of them as enabling technology for the development of a dedicated solution.

The replication of the human unloading, item by item, using a dual arm manipulator with dexterous hands would be an interesting experiment with an application potential to very small craft productions in sectors processing expensive materials for highly profitable applications, such as prototyping of seating and furniture, the manufacturing of interiors of high-class cars, executive aircraft, boats, the manufacturing of tailored suits.

Main requirements for the picking handling system are a very high MTBF (five years continued use) and high acceleration and velocity to make the handling cycle time compatible with the average cutting times and the handling technologies developed in *CloPeMa* will help to achieve these performances.

6.2 Mould loading for 3D joining

A direction of development in the automated manufacturing of items made of compliant materials is the 3D joining. Traditionally, the joining is performed in a developed or flat state along planar sewing paths. The well known traditional joining performed from flat is the sewing, which involves a very high dexterity that today only humans (and well trained) have. The changing of the joining technique does not change the procedure: welding and bonding are still performed along planar paths.

A radical change in the method is the joining in 3D. The items are loaded on a 3D mould, hold in position and joined by a robot moving the joining device (sewing head or any other type). The loading of the mould is difficult; it requires dexterous handling of the items and their accurate positioning on the mould; the edges must be prepared for the joining. The limit to the diffusion of 3D joining is that the positioning of the items can be performed today by human operators only. The results of *CloPeMa* may contribute to the automation of the mould loading process making the 3D joining an industrial option to the methods in use.

6.2.1 Seats for transport (trains, cars, aircrafts)

The manufacturing of 3D shaped products assembled from flat flexible materials like the transport system interiors (seats, head and arm-rests etc. for automobiles, aircraft, busses, trains, cruise ships), which all represent large and growing markets at global scale is today mainly based on human work and could really benefit of the results of *CloPeMa*. In effect, some of the aforementioned cases up to 60% of the final product cost is associated with labor cost to perform short duration and highly repetitive tasks which determine a considerable psychical and physical strain on the worker.

The overall process is highly time consuming (60% of overall manufacturing time) and is deeply depending on the skills of the operators. Alternative methods for joining natural and artificial fabric or leather parts together have been introduced, including fusing, scatter coating, dry dot printed coating, paste coating, welding (ultrasounds, laser) and adhesives. However all these joining methods still rely on labor intensive tasks to handle and position the fabric pieces on the specific molds or structural frames as well as to operate the equipment. *CloPeMa* proposes a new way to handle the soft parts and sub-assemblies in an autonomous and semi autonomous way, by performing, if needed, cooperative tasks with humans.

The tasks where the *CloPeMa* technology could be directly applied are the preparation of the covers of the seats and the dressing of the seats. The preparation of the covers could be performed using 3D assembly on mould as described in Section 6.2. The dressing consists of inserting the preassembled enveloped on the body of the seat with the padding already in position; the dressing is pulled and accommodated to adapt to the shape of the seat body with a residual strain. The operation involves the use of the hands to adjust the padding while the envelope slides over.

6.2.2 Furniture

The most relevant market is the one of seats, sofas, chairs and bedding. Today the products on the market can be roughly divided in two classes: handmade and high-quality expensive *pieces of artistic design*, and mass-manufactured. The high-class items may have more complex structures since they are practically handmade; the personnel applies traditional manufacturing processes, in particular the 2D sewing which is the most time and effort consuming. The mass-manufactured are designed taking the manufacturing process into account and this limits the design to shapes and structures that can be produced automatically or that involve simple manual operations. It is quite usual that the covers, which are very personnel-consuming, are produced in regions where the cost of the personnel is lower and are then transferred where the overall assembly is done.

The gradual availability of robots able to perform operations that today are carried out manually may progressively make closer the high-quality and the large-market productions: on one hand, the cost for small batches and mass-customized items may reduce, and, on the other hand, the mass-manufactured items may have more complex designs and their production in countries with higher personnel cost may become sustainable. The widening of the market of items with artistic design made possible by a reduction of their manufacturing costs may open a relevant potential market in the western countries and especially in Europe, where the knowledge economy is at the base of the sustainability of a competitive industry.

6.3 Handling of fibre layers in composite manufacturing

The results of *CloPeMa* will allow to solve the problem of the manipulation of difficult materials such carbon fibre and composite opening new automation and robotization processes in the aeronautics and related industrial sectors that are vital for Europe. In effect the availability of reliable handling solution will extend the application of flexible automation and robotics that will help keeping these manufacturing sectors in high wage countries like Europe. Example application is the realization of new hyper-flexible cell for handling carbon fibre preforms, served by two cooperating robots, endowed with ”plug & produce” capabilities, able to pick parts with different geometries from a cutting table and to place them on moulds with different 3D shapes.

6.4 Padding and further application areas

Further application areas that can benefit directly or indirectly of the *CloPeMa* results are the ones of the finishing and packaging of soft products. The manufacturing skills involved comprise and extend the ones for seat manufacturing. The padding must be grasped, handled, positioned, adjusted, accommodated.

Other application areas for the *CloPeMa* handling skills are in the medical and biomedical/biological sectors, in manipulation and processing of tissues. The closest outcomes deal with the production of tissues in controlled conditions in vitro, where soft layers have to be grasped and manipulated repetitively during the production and packaging.

6.5 Impact

The targeted industrial end users represent the biggest relevant markets for assembled 3D, single and multilayered textile-based products with estimated end market sizes of over 10 bn Euros for functional and protective clothing, 11 bn Euros for aeronautics, 7 bn Euros for automotive and other transport interiors, 3 bn Euros for light-weight constructions (roofings, covers, tents and inflatables) and up to 2 bn Euros for filter applications used in medical and a wide range of industrial applications. Global growth rate are high, especially in the emerging countries (China, Russia, India, Brazil, Turkey or the Middle East) in which attractive export opportunities exist for European companies. The involved end users are the or among the European market and innovation leaders, whose innovations usually trigger industry-wide technology transitions.

The expected technology breakthrough in intelligent two-hands handling and assembly of soft material products tackles simultaneously the 2 main drivers for sustained competitive leadership of European companies - manufacturing efficiency and product quality. The remaining substantial labour cost component due to manual or semi-automatic assembly processes constitutes a vulnerability of European market leaders which can be exploited by competitors in low-cost countries, but should be alleviated through more intelligent automated assembly.

If the problem of intelligent automation of industrial processes involving soft materials becomes feasible and reliable, this will ensure enhanced value added and at the same time faster reaction to market requirements.

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