Human robot collaboration for folding fabrics based on force/RGB-D feedback

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Abstract. In this paper, the collaboration of a human and a robot for executing complicated handling tasks for folding non-rigid objects is investigated. A hierarchical control system is developed for the co-manipulation task of folding sheets like fabrics/cloths. The system is based on force and RGB-D feedback in both higher and lower control levels of the process. In the higher level, the perception of the human's intention is used for deciding the robot's action, then in the lower level the robot reacts to the force/RGB-D feedback to follow the human guidance. The proposed approach is tested in the folding of a rectangular piece of fabric. The experiments showed that the developed robotic system is capable to track the human's movement in order to help her/him to accomplish the folding co-manipulation task.

Keywords: human robot collaboration, folding, cloths, force/RGB-D control, human intention, co-manipulation.

1 Introduction

In the industrial and craft sectors as well as in domestic and agricultural domains there are various tasks where two humans are needed to manipulate a non-rigid object. In cloth/carpet/upholstery/awning industries such tasks are transportation, handling and folding of long fabric sheets [1]. Moreover, similar tasks are found in automotive assembly such as: upholstery of seats, carpets and long cables or in robotic space applications such as blanket manipulation for satellites. Other cases can be found in the handling of sheets for laying-up the plies of a composite material object. The folding of fabrics by people with disabilities sometimes is a difficult task and especially in cases where only the one hand is functional. Despite the challenges for great research opportunities into this scientific field, the automation of such tasks is still rudimentary.

The robotized manipulation of non-rigid and highly flexible sheet like objects is a very complicated problem due to their very low bending resistance, their large deformations and their materials' non-linearity [2]. This kind of objects can change their shape by twisting, buckling, folding and wrinkling due to gravity. It is often said that they have "infinite" degrees of freedom since it is very hard to define how many are needed to define their configuration.

The approaches and the research efforts, to build robotic systems for handling fabrics, considered one robot [3, 4] or two cooperative robots[1, 2, 3] [5, 6, 7]. These approaches were based on fabric state recognition using mainly vision sensing, or on predefined folding motions that are based on humans' motion analysis [4], or on high speed dynamic folding without table and using cloth models [5], or on a combination of the above concepts [6, 7]. Most of these approaches, besides their needs for knowing or identifying the state/model of the fabric, are not directly applicable for folding fabrics with larger dimensions.

In an alternative viewpoint, the robots cooperate with humans, which are the leaders, while the robots assist them, that could be applied in domestic or industrial fabric handling tasks. The concept of the human-robot cooperation for moving a piece of fabric, along one direction, was presented in an earlier study [8]. In that work, the motion of a piece of fabric along a line was based on a neural network controller and compared to a PID controller. The human was the guider for this simple handling task and the robot followed him ensuring a constant tension on the fabric. Later, that was extended to the transportation of the fabric along the main directions of a fixed Cartesian system [9].

In the present paper, a two level hierarchical control system is proposed, based on human robot collaboration for co-manipulation of sheet like fabrics. The higher level deals with the perception of the human's motion, and the decision making for the determination of the robot's grasping point. In the lower lever, the co-manipulation handling task is implemented by a hybrid force/RGB-D feedback controller. The folding of a rectangular piece of fabric is presented as a case study. In the next sections, the proposed approach for the fabric folding task is described. The two levels of the hierarchical system are presented in sections 2 and 3. The experimental results and the efficiency of the proposed system are presented in Section 4, while the prospects of the system are described through the future work in the last Section 5.

2 Fabric folding based on human-robot collaboration

The autonomous accomplishment of a very complex and demanding handling task, such as the folding of a fabric, requires systems that should have high flexibility and intelligence to plan the motions. Thus, the collaboration of a human-robot, where the human acts as the guider and the robot follows, is proposed. A folding handling task according to the proposed approach is shown in **Fig. 1**, where a human and a robot are collaborating for folding a piece of fabric that is laid on a table, which could be a towel or a tablecloth.

For the reduction of the possible fabric's configurations the well-known gravity-table pair is considered. It is also assumed that the model of the fabric is unknown due to the difficulties in fabrics' modeling. Likewise, the identification of the configuration and the state of the fabric, i.e. unfolded, wrinkled or not, folded with one or more folds etc., are not responsibilities of the control system but are duties of the human, who acts

[1] Rethink Robotics, http://youtu.be/Mr7U9pQtwq8
[2] CloPeMa research project, http://youtu.be/gK7yuPfzuD4
[3] UC Berkeley Folding Robot, http://youtu.be/gy5g33S0Gzo

as the task leader. Our aim is to develop a robotic controller for co-manipulation of a variety of fabric types without any prior knowledge about the fabrics model and its properties, but to be able to co-manipulate only through the recognition of the intention and the actual movements of the human.

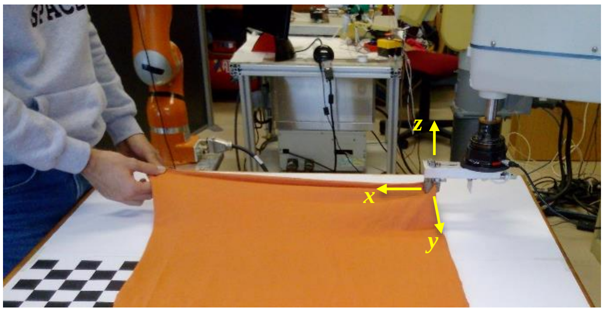

Fig. 1. Human robot collaboration for folding a fabric.

An RGB-D sensor is used for identifying the configuration of the human and a vision sensor is used for localizing the fabric. A decision making system is proposed to deduce the human's intention in terms of how she/he wants to handle and fold the fabric. The system decides the appropriate robot grasping point on the fabric to accomplish the folding subtask implemented in the lower level. In the co-manipulation phase, the robot is synchronized with the human through a hybrid force/RGB-D controller.

3 The two level hierarchical control scheme

The state transition diagram of the hierarchical sequence of Perception – Decision making – Decision execution – Co-manipulation is designed, for realizing the fabric folding task, as shown in **Fig. 2**, where the states of the human-fabric-robot system are represented. The process starts with the state (A) where the human's hand moves towards the fabric. The loop (H_{motion} at state A) ends and the state of the system is changed to state (B) when the human grasps the fabric (H_{grasp}). At this point the intention of the human, concerning the next folding sub-task, is deduced, and the robot positions its end effector in order to grasp the fabric (R_{motion} at state B). The loop terminates when the robot grasps the fabric and the state of the system is transferred to state (C). In state (C) the lower level of the hierarchical control is taking place. The robot follows (R_{motion} at state C) the human's actual motion (H_{motion} at state C) under force/RGB-D feedback. This action, results to a folding of the fabric according to the guidance provided by the human. If the human wants many folds of the same fabric the above described procedure is repeated when the human simply releases the cloth (state transitions back to A).

3.1 Perception and decision making *(higher level).*

In the higher level of the control scheme, the perception of the human motion and the inference of the human intention take place. The shape of the cloth, as well as the human gripping point and his/her configuration could be a basis for correctly deciding the intended folding. Once the folding configuration is understood, the robot gripping point can be calculated and sent to the robot to start the co-manipulation.

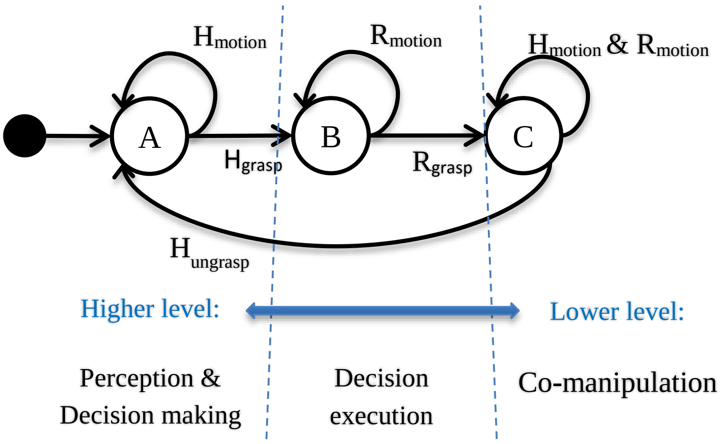

Fig. 2. The hierarchical controller and the state transition diagram for the folding task.

Human pose/intention based on RGB-D sensing

Experiments were performed with humans on collaborative folding without having the ability to verbally communicate with one another so as to understand each other's intention. After that the participants were asked to describe how they concluded what the other human intended to act. In the fabric folding process, there are two major criteria that were employed to identify the human's intention; tracking of the gripping hand position and tracking of the person's torso orientation.

This result was very close to our initial guess, since a human prefers to maintain a high dexterity across the direction of his intended motion, which is normal to his torso orientation. Also, considering the fact that psychological reasons might apply when cooperating with an industrial manipulator, the human will choose to keep his point of view towards the robot for safety reasons (keeping his eyesight always opposite). These assumptions could suffice in the fabric folding tasks, given the fact that the robot has a robust decision making mechanism that can understand the required folding procedure.

The localization of the fabric plays also a major role in the cooperation. The identification of the fabric configuration is a very complicated task. However in our scenario the human's intellectual ability is much greater than the computational power provided by a machine learning algorithm. Therefore, it is assumed that the human has the fabric laid on a flat surface for the robot. The RGB-D sensor can be used for the localization process as well - if the cost is to be kept to a minimum - however an additional low cost camera is used for better results and to place the two sensors in an optimum location. Machine learning algorithms or lookup tables could be considered for decision making in complicated fabric folding tasks.

Robot action according to human intention

After the decision making process that determines the fabric location and robot grasping point, the decided robot motion executed (intermediate level as shown in **Fig. 2**). The robot approaches the desired point of the fabric from the top and grasps (pinches) the fabric. For this sub-task a force-position controller is developed, where the force part (along the z axes) is responsible for approaching the table, until a predefined force is measured. The gripper direction points to the corresponding point that has been grasped by the human, as shown in **Fig. 1**. After this level, the robot is ready to follow the human's movement controlled by a hybrid force/RGB-D controller.

3.2 Co-manipulation based on the hybrid force/RGB-D robot control *(lower level)*

The folding of the fabric is accomplished with a synchronized motion of the human and the robot hands. In this lower level hybrid control scheme (**Fig. 3**), for the co-manipulation, the RGB-D system (*Vision/Depth–feedback)* is tracking the human's hand and the force sensing system (*Force–feedback)* measures the actual forces that are applied to the fabric. The motion of the robot end-effector, along the main axes, is guided by the combined outputs of the force and RGB-D feedback controllers, as:

Robot position: direction, axis	+x	-x	+y	-y	+z	-z
Controller: *Force* (*F*), *RGB-D* (*V/D*)	*F*	*V/D*	*V/D*	*V/D*	*F, V/D*	*V/D*

The x, y, z-axes are for the tool frame, i.e. the coordinate system shown in **Fig. 1**. The motion of the robot along the +x direction depends only on the force controller, since when the human pulls the fabric then the force signal is more significant than the RGB-D one. Along the other directions, the fabric resistance is negligible and therefore the measured forces are very low, while the vision/depth feedback signal is significant. Finally, for the motion along the +z direction both the force and the RGB-D controllers contribute to the end-effector motion, however, the force controller has the priority to prevent collision of the robot with the table.

RGB-D feedback (*V/D*) for the co-manipulation during folding

The skeleton tracking library used can track the configuration of the most significant joints in the human body. However, due to the nature of the sensor as well as the intended use of this software, the accuracy of the algorithm can be compromised, leading to a significant position error that could damage the process. To overcome this problem, a moving average filter has been used that filters out large displacements over small time steps. This filter however causes an increase in the time constant of the controller, which however is acceptable due to the nature of the cooperative task.

The interface between the RGB-D servoing controller and the manipulator is for a two way communication, allowing the high-level controller to correctly identify the state changes from state C to state A (when the human releases the fabric). This is identified when the distance between the hand and the end effector increases (over a tuned threshold), and no significant change in the force is measured.

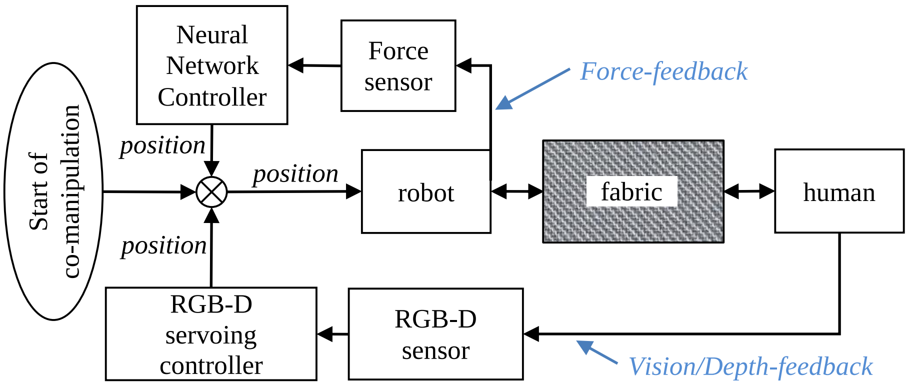

Fig. 3. Hybrid Force/RGB-D control scheme.

Force feedback (*F*) for the co-manipulation during folding

The force feedback controller consists of a neural network controller as shown in **Fig. 3**. A feedforward neural network with a simple topology, composed by three layers with the configuration (1-6-1) has been used as described in [8, 9].

4 Experiments and results

The Adept Cobra s800 robot is used for the experiments. The forces are measured using the F/T system (Gamma 65/5) from ATI Industrial Automation, which is mounted on the wrist of the robot. The RGB-D sensor is the Asus Xtion while for the fabric localization a simple low cost USB webcam is used. The perception and the decision making processing of the higher level is implemented in C++ and running in ROS [11] with OpenCV [12] (for the fabric localization) and NITE2 [10] with OpenNI2 drivers, publicly available at bitbucket. The high level controller is implemented in a PC and communicates with the robot controller via a serial interface. The low level controller, including the force control scheme, is implemented directly on the Adept SmartController CX.

To demonstrate the capabilities of the proposed controller, the task of folding a rectangular piece of fabric is tested[4]. The fabric is laid on a flat surface, and a calibration pattern is used to identify the extrinsic parameters of the camera with respect to the surface of the fabric. The coordinates of the four vertices of the fabric are calculated using a simple threshold filter and sent to the high level controller as shown in **Fig. 4**. Concurrently, the RGB-D sensor tracks the human configuration and performs a nearest neighbor query to identify whether his hand is close to any of the fabric's vertices.

The controller does not monitor the actual grasping movement for simplicity; instead it assumes that the human has performed the grasping if his hand is not moving for a short period of time, while still being close to the fabric vertex (shown in **Fig. 5**), for

[4] A demonstration of the folding task can be viewed in the Robotics Group YouTube channel

two different grasping configurations of the same fabric. The yellow sphere shows the identified vertex grasped by the human while the white sphere shows the commanded vertex that will be grasped by the robot's end effector. The green sphere shows the actual human hand position as identified by the RGB-D sensor.

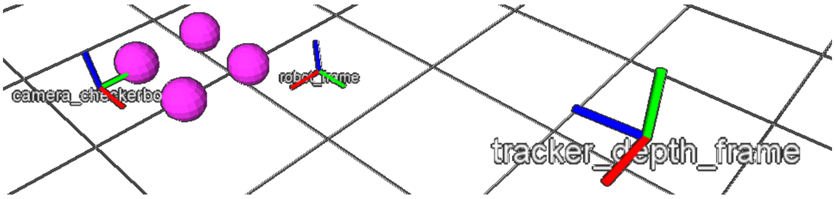

Fig. 4. The coordinate frames of the robot, RGB-D sensor and the camera extrinsic calibrated fabric coordinate frame. The purple spheres indicate the four identified vertices of the fabric.

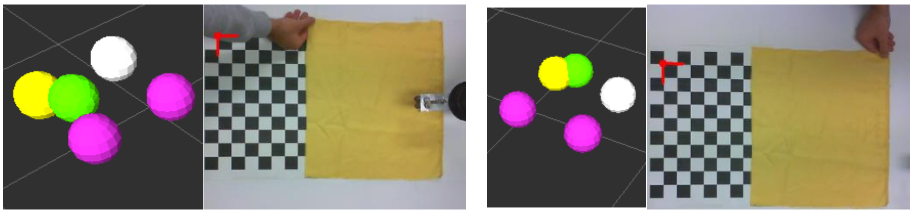

Fig. 5. Two grasping configurations for the same fabric (left: 3D model and right: camera feed).

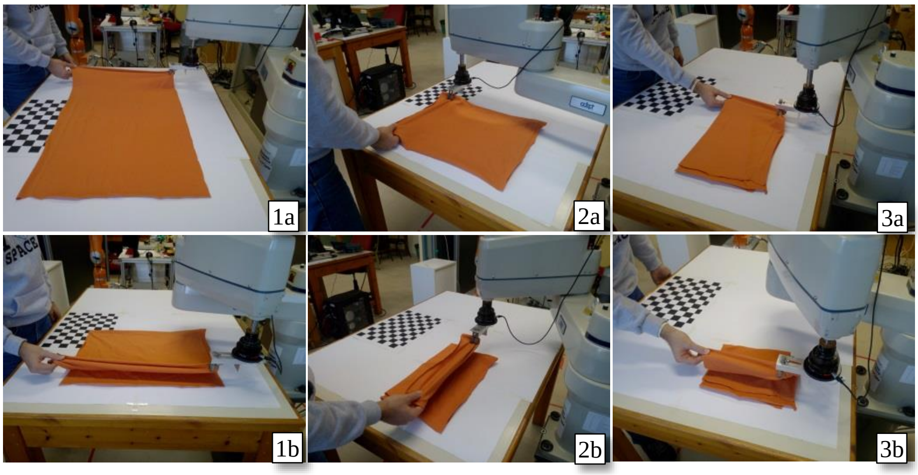

Fig. 6. Photos taken during the folding process after three consecutive folding motions.

In **Fig. 6**, the fabric is folded in 8 layers (1a-1b-2a-2b-3a-3b) in three stages. This folding is the conventional one that is followed when folding tablecloths, bedsheets and towels. The states of the higher level (perception-decision making and execution) are in the top pictures (1a, 2a, 3a), where the human and the robot grasp the fabric. At the end of the co-manipulation (lower level) the states of the fabric are shown in the bottom pictures (1b, 2b, 3b), where one fold of the fabric has been completed. The transition from the one fold to the other (1→2, 2→3) is performed, if the human stops her/his movement and ungrasps the fabric, while withdrawing his hand towards his torso.

5 Conclusions and Future Work

The collaboration of a human and a robot for folding rectangular pieces of fabrics is presented in this paper. The proposed hierarchical control based approach is presented in detail and the experiments show that the co-manipulation for folding is achieved.

Our future research directions, of this work, are focused on the development of a sophisticated decision making system for complicated folding sequences, on the investigation of the robustness of the system and its speed response, as well as on the incorporation of the torques in order to involve the pitch/roll/yaw movements of the robot.

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