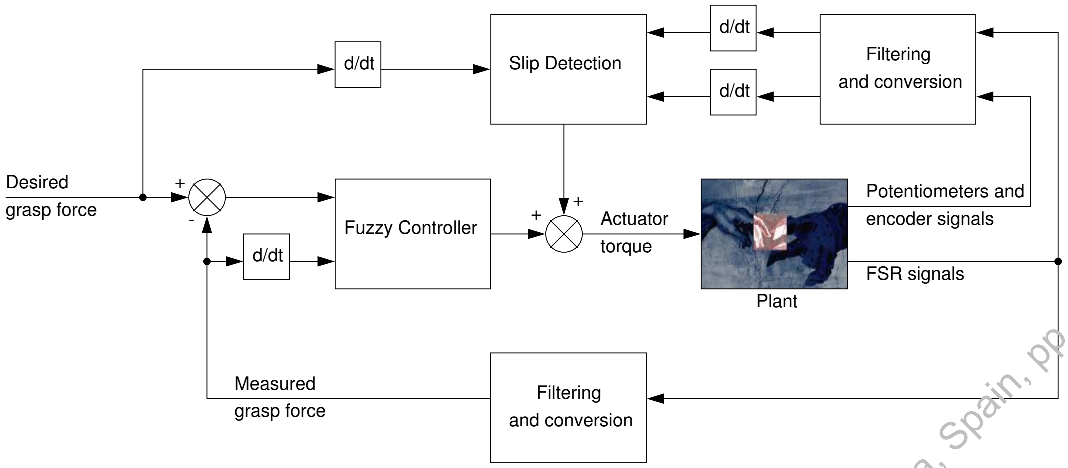

Fig. 8
CONTROL SCHEME OF THE FINGER.

force value when slippage occurs, a similar result has been reported in [19]. This variation comes without any motion of the finger itself which is thus still grasping what appears to be a motionless object. Furthermore, no change in actuator torque has been requested. Thus one has the situation of a motionless object, grasped with a constant actuator torque but the tactile sense of the hand records a quick decrease of the force applied. This phenomenon can only be explained either by a local deformation of the object or by slipping. Both cases require a different handling. For instance if the object is locally starting to deform, that means that the object is breaking down, the grasp forces should therefore be decreased. On the contrary, if the object is slipping, grasp forces should be increased to prevent the object from escaping. In fact this dilemma is not solvable without *a priori* knowledge or extra information. From an experimental point of view, slippage is detectable, even with cheap, off-the-shelf sensors like FSR. However, a 100% success rate can not be ensured, and may depend on the material combination. An example of slippage with a power grasp is illustrated in Fig. 7, similar results are found with pinching precision grasps. Note that the sensors' values are usually not the same before and after the slippage. The event "slippage" has been described as corresponding to: a short-time variation the phalanx forces, a constant actuation torque, no motion of the finger. To detect the motion of the finger, one has to use the data provided by the potentiometers and the actuator's encoder. Indeed, the latter is not sufficient to detect a motion of the finger since the finger can move with its actuator locked: this feature is mandatory to obtain the shape adaptation behaviour. In response to this event, an anti-slippage scheme has been implemented that increases the actuation torque as soon as these characteristic conditions are fulfilled. The magnitude of the increase has been experimentally determined to be a jerk increase of 10%, mimicking the reflex action of a human being, and is added to the force control component of the command. This superposition of the commands has also been reported to be the principle behind human prehension [20]. Since both commands are to be added, the influence of the fuzzy force controller should be taken into account. Indeed, the force controller detects the decrease of the grasping force and tries to counter the latter. The fuzzy force controller is however too slow to actually prevent slippage. An illustration of the complete control scheme is presented in Fig. 8.

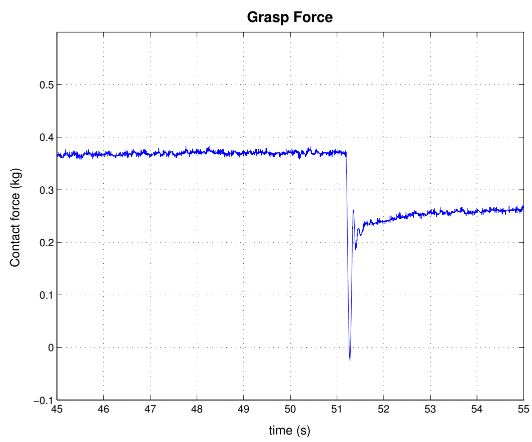

Fig. 7
TYPICAL SENSOR OUTPUT DURING A SLIPPAGE (CYLINDRICAL POWER GRASP, FILTERING ACTIVE).

V. CONCLUSIONS

To conclude this paper, it can be noted that promising experiments have been conducted with tactile sensors on

TABLE I

HARDWARE COSTS.

Item	Units	Price (US$)
FSR	8	28
DB cables	3	40
electronic board	1	15
components (IC, resistors, etc.)	-	20
power supply	1	20
Total		≤ 125

an underactuated finger and yes, the behaviour of underactuated fingers can be substantially enhanced with tactile information. Underactuated fingers may even be a predilection type of hands for the use of tactile sensing since the simplicity of the initial controller leaves significant computation time to process the tactile data in real-time. However, the use of tactile sensing with underactuated fingers has rarely been reported [14], [15].

Experimental force control has been implemented with very good results using a fuzzy logic controller with sufficient finess to hold an egg together with a person and move it with a pinch grasp (cf. Fig.9). It should be noted that this hand was designed for industrial applications and can lift more than 70 kg, much more than what is required to crush the egg. Prevention of slippage has been built on top of the previous controller. One should note that the total cost of the hardware required to achieve this intelligent behaviour (see Table I) is very limited and negligible compared to the machining cost of a finger. Another aspect that can be of interest and has not yet been investigated is object recognition using tactile sensor data.

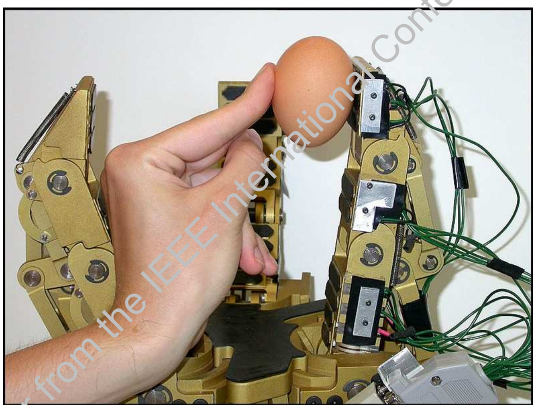

Fig. 9

FORCE CONTROL EXPERIMENT: HOLDING AN EGG IN COLLABORATION.

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