Using Configuration and Force Sensing in Assembly Task Planning and Execution *

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Abstract

A geometric trajectory ensuring the success of an assembly task cannot be determined when the geometric uncertainty is significant. Several solutions like, for instance, passive compliance devices have been applied in order to decrease the influence of geometric uncertainty. Nevertheless, the general solution appears to be the use of active compliance which implies reaction force/torque feedback, but this use gives rise to some particular problems in the task planning and execution. Sensorial configuration and force information becomes a key point in this field. This paper describes how this sensor information can be used in an assembly fine-motion planner and also during the task execution. The basic concepts have already been implemented and the peg-into-hole assembly task serves as an example to illustrate the results.

1 Introduction

The automation of assembly tasks with robots can be problematic due to the geometric uncertainty, since it does not allow the off-line programming of a geometric trajectory ensuring the assembly success.

A first solution was the use of passive compliance devices, (e.g. the Remote Center Compliance device) and an improvement on the object design (e.g. the use of chamfers). Later, the use of active compliance strategies based on the feedback of the sensed reaction forces and torques appeared to be a more general solution.

In this context, the automatic determination of the robot movements to perform an assembly task in the presence of geometric uncertainty has become an interesting research field, often known as fine-motion planning [11], [6], [18], [10], [8], [15], [5]. Generally, a fine-motion plan does not describe geometric trajectories explicitly, but as a function of the current actual situation during the assembly task execution. Besides the information on the configuration, the current situation could be estimated by using, explicitly or implicitly, reaction force information in order to decrease the uncertainty in the contact surface orientation, and reaction torque information to reduce the uncertainty in the contact position.

Within this frame, this work deals with the use of configuration and reaction force/torque information in assembly task planning and execution. The paper is organized as follows. After this introduction, section 2 briefly describes a fine-motion planner previously proposed by the authors [14]. Sections 3 and 4 are centered respectively on the off-line (prediction) and on-line (estimation) use of configuration and reaction force/torque information. Section 5 illustrates the theoretical developments by means of a 3 d.o.f. peg-into-hole example. Finally, section 6 summarizes some conclusions of the work.

2 Fine-motion planner

The above mentioned fine-motion planner is based on the representation of the assembly task by a graph of states, and on the determination of the operators (robot commands) to produce the transition from one state to another. The planner selects in the graph a sequence of states going from the initial state to the desired goal; thus, during the task execution it is only necessary to identify the current state and apply the corresponding operator to progress in the states sequence.

Several planners work in a similar way, the difference between them being the way in which the states are defined and the operators determined, which leads to the application of different criteria during the planning and execution phases.

In the authors' approach a *task state* E is characterized by a set of compatible basic contacts [14], [2], [15]. The states constitute the nodes of a graph *G-Nom* whose arcs link contiguous states.

Each state E has a *realization* R, the set of configurations in which E takes place for some given parameter deviations. Since it is not possible to exactly know the actual deviations, the *real* realization of a state for a particular task execution cannot be determined. Instead, it is possible to get a *nominal realization* Rn from the nominal values of the geometric parameters. The union of the nominal realizations Rn is equivalent to the nominal contact configurations in the Configuration Space ($\mathcal{C}$) and therefore *G-Nom* is equivalent

*This work was partially supported by the CICYT project TAP93-0415 and the ESPRIT Project B-LEARN II under contract n^{o}7274. J. Rosell has a grant from the Catalonia Government.

to the graph describing the topology of the nominal contact space. Although the actual realization R of a state E cannot be determined, it is possible to establish the region of $\mathcal{C}$ in which it should be, and then by adding the sensor uncertainty, determine the configuration domains in which E can be detected.

The *state transition operators* T are characterized by a direction[1] in $\mathcal{C}$ that may produce the transition between two given contiguous states.

The plan is composed of two main modules. The first one, called *states_to_operators*, is built by selecting in *G-Nom* a sequence of states linking the expected initial state with the final desired one, and choosing a proper set of operators T allowing to follow that sequence. Since, due to uncertainty, operators T cannot ensure a given transition, the original sequence is expanded into an oriented subgraph *G-Plan* of *G-Nom*, maintaining a unique terminal node: the desired goal state. The second module, called *sensing_to_states*, is built by merging the different uncertainty sources to determine the possible sets of configurations and generalized forces (forces and torques considered simultaneously) that can be observed in each state during the task execution. These sets, called *observation domains*, will be detailed below. The fact that the corresponding sensor measurements belong to the observation domains constitutes the criterion for the on-line estimation of the current state. Figure 1 shows the flow from the initial information to the two modules of the plan.

The task execution following the plan consists basically in the repetitive performance of two actions (figure 2): identifying the current task state E and applying the corresponding operator to progress toward the goal state in *G-Plan*.

Uncertainty is to be considered off-line in the determination of the realization sets and of the operators T included in the plan, and also for the on-line identification of the current task state using sensor information. The following sections describe in detail how configuration and force information is used for this purpose in the presence of uncertainty.

3 Use of configuration information

In the absence of uncertainty, the configuration information is enough to plan and execute the assembly task. Although this is no longer true when geometric uncertainty becomes relevant, it remains being basic information.

The following geometric uncertainty sources must be modeled and taken into account:

a) tolerances in the object shape and size
b) imprecision in the positioning of the objects in the workspace
c) imprecision in the robot position and orientation
d) imprecision in the positioning of the object in the robot gripper. It depends on the uncertainties from sources b and c plus undesired slippings of the object in the gripper; nevertheless, it can be considered as a source itself since the grasping operation can reduce these uncertainties.

[1] From now on direction means direction and sense

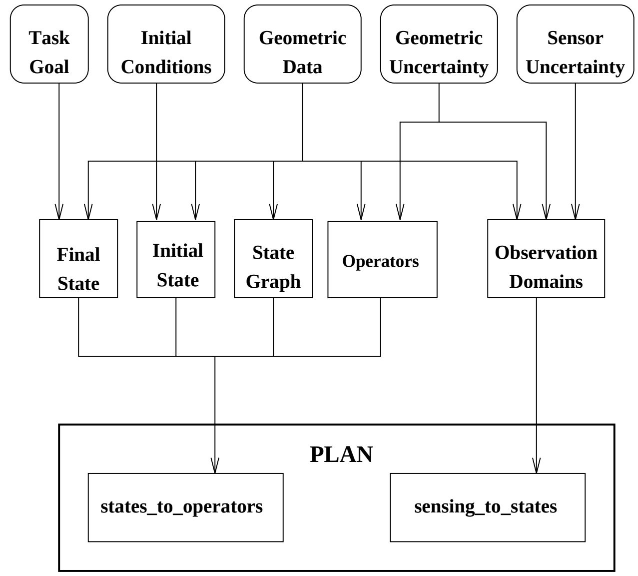

Figure 1: *Planner flow diagram.*

All these geometric uncertainty sources are merged in the physical space in order to determine the uncertainty regions where the vertices, edges and faces of each object will really stay. By establishing contact conditions between the objects, these domains are mapped into Configuration Space, giving rise to an uncertainty domain for each $\mathcal{C}$-surface (entities of dimension $n-1$ for a n-dimensional problem) and representing the set of configurations where a basic contact can happen.

Considering geometric uncertainty, the following two sets of configurations are of interest:

- *Configuration realization domain DCr:* configurations where a given state E can take place; it is obtained by merging uncertainty sources a, b and d.
- *Configuration observation domain DC:* configurations that can be sensed when a given state E takes place; it is obtained by adding the uncertainty source c to DCr.

The domains DCr are used off-line to determine the set of possible state transition operators between any two contiguous states. Basically, the operators allowing to leave or to reach a given state are determined by analyzing the directions in $\mathcal{C}$ crossing a given portion of the corresponding DCr frontier [15].

The domains DC are used on-line to determine which states are compatible with the current sensed configuration. This is done by selecting the states whose domains DC contain the sensed configuration. Obviously, due to uncertainty, more than one state could be compatible with the current sensed configuration, so the analysis of reaction forces becomes necessary.

The modeling of the uncertainty sources for three degrees of freedom tasks and a procedure to compute the domains DCr and DC have been proposed in [1]. The results of that work are applied below in the example of section 5.

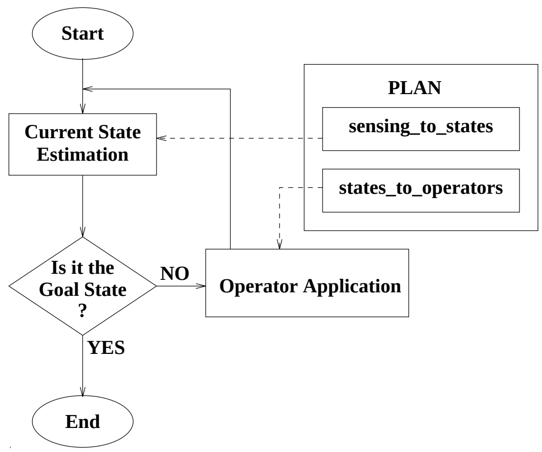

Figure 2: *Task execution according to the plan.*

4 Use of force information

The knowledge of the generalized reaction force is the natural complement to configuration information in the presence of geometric uncertainty, since a reaction force indicates a constraint in Configuration Space. Only the direction of the generalized reaction force is of interest, its module being irrelevant.

The direction of a generalized reaction force is affected by the geometric uncertainty sources already introduced in section 3 and by the imprecision of the force/torque sensor.

In this context the following two sets of generalized forces are of interest:

- *Force realization domain DGr:* generalized forces that can take place in a given state E. This set of generalized forces is determined by merging the effect of friction and the geometric uncertainty on the direction normal to the object contact face.
- *Force observation domain DG:* generalized forces that can be sensed when a given state E takes place; it is obtained by adding the uncertainty of the force/torque sensor to DGr.

The domains DGr are used off-line as a complement to domains DCr for the determination of the state transition operators T. In a given state E, operators with a direction belonging to the corresponding domain DGr must not be used in order to avoid jamming in E.

Domains DG are complementary to domains DC for the on-line determination of the possible current state. When more than one state is compatible with the sensed configuration, they are pruned by selecting only those whose domains DG contain the sensed generalized reaction force. It must be noted that the domains DC and DG of more than one state could be compatible with the sensed data; if so, the present sensor information *is not enough* to unambiguously identify the task state. In this case different solutions are possible, such as the execution of a test-movement in order to obtain more information [7], [13], but this is a complex and time-consuming operation and it may also alter the desired plan evolution. Another approach makes use of the knowledge of the previous states in order to try to remove the ambiguity. In this line it is possible to establish heuristics for each particular case.

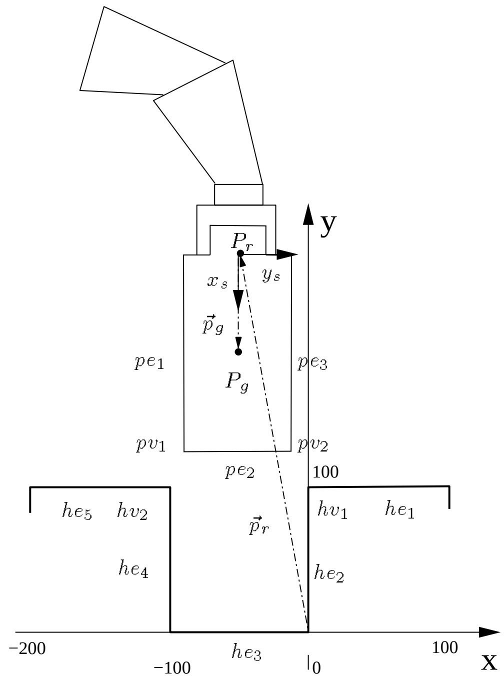

Figure 3: *Peg-into-hole assembly task.*

The domains DGr have been computed in the absence of uncertainty using the theory of polyhedral convex cones [9].

Considering the different sources of uncertainty, a methodology to compute the domains DGr for three degrees of freedom tasks has been presented in [16], and a procedure to determine which domains DG contain a given measured generalized force without explicitly building the domains DG are described in [3]. The results of these works are applied below to the example in section 5. Some heuristics to estimate the current contact state in the case of ambiguity for the planner described in section 2 has been proposed in [15].

5 An example

The concepts presented in previous sections are illustrated here using a planar peg-into-hole assembly task (figure 3). The widths of the peg and the hole are 80 mm and 100 mm respectively. Although the clearance seems to be large, the geometric uncertainties are taken of the same order. The origin of the gripper coordinate system P_r is located on the gripper symmetry axis at the end of the fingers. The position of P_r in the world reference system is given by $\vec{p}_r$, and the absolute orientation of the gripper symmetry axis with respect to the x-axis by ϕ_r (in figure 3: $p_r = 275$ mm and $\phi_r = -90^o$). The position of the peg in the gripper is described by vector $\vec{p}_g$, which locates the peg reference point P_g in the gripper coordinate system. In the example, $\vec{p}_g$ is characterized by $p_g = 70$ mm and $\phi_g = 0^o$. The force/torque sensor is mounted on the robot wrist, and its measurement reference system is centered on P_r with the x_s-axis aligned with the gripper symmetry axis, as shown in figure 3; clockwise torques are considered negatives. The friction coefficient μ is assumed to be constant and equal to 0.1.

The uncertainty sources are:

Uncertainty in the shape and size of the objects: each vertex is constrained to be inside a circle with a radius of 3 mm centered on its nominal position.

Uncertainty in the absolute position of the static object: each vertex is constrained to be inside a circle with a radius of 5 mm centered on its nominal position.

Uncertainty in the robot positioning: P_r is constrained to be inside a circle with a radius of 1 mm centered on its nominal position, and the maximum deviation of the orientation is 2^o.

Uncertainty in the positioning of the peg in the robot gripper: P_g is constrained to be inside a circle with a radius of 6 mm centered on its nominal position, and the maximum deviation of the orientation is 2^o.

Uncertainty in the force/torque measurement: the actual value of each force component is constrained to be inside a range of 0.2 N centered on its measured value, and the actual torque within a range of 0.002 Nm around its measured value. Therefore, the head of the actual generalized force vector is inside a parallelepiped in 3-dimensional force space.

The vertices and edges of the objects are named as shown in figure 3. The following task states will be used in the example:

state	contact #	vertex-edge	type
E_1	1	pv_1-he_4	1
E_2	2	pv_2-he_3	1
E_3	3	pv_2-he_1	1
E_4	4	hv_1-pe_3	2
E_5	1, 4	pv_1-he_4, hv_1-pe_3	1, 2
E_6	1, 2	pv_1-he_4, pv_2-he_3	1, 1

5.1 Configuration domains

The resulting uncertainty regions of the object vertices and edges in the physical space after merging the geometric uncertainties above mentioned are shown in figure 4a and in the pictures of column A in figure 5, for different peg orientations (for clarity, the uncertainty domains of the peg edges are not drawn).

A basic contact between a vertex and an edge is possible only for the set of configurations corresponding to the intersection in physical space of the uncertainty regions of the vertex and the edge. The boundary of this intersection is computed by establishing a symbolic contact condition for the maximum deviations allowed by the uncertainty, and by solving it for position or orientation depending, respectively, on whether the basic contact is type 1 or 2 (i.e. leaving

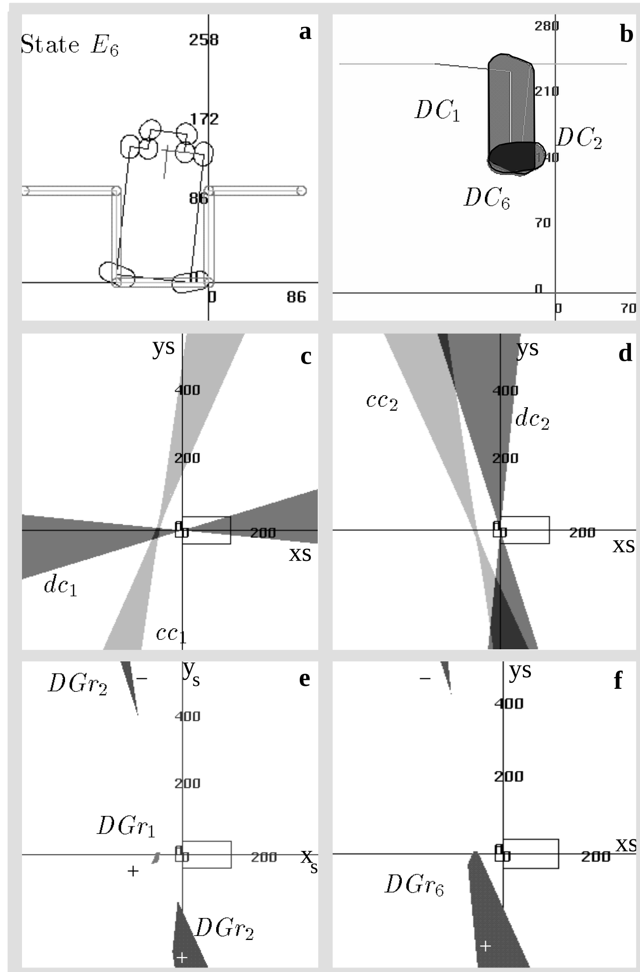

Figure 4: *Examples of physical space (a), configuration domains (b) and force domains (c,d,e,f), for* $\phi_r = -96^o$

the orientation or position of the peg as a parameter). So, a sliced configuration space is obtained containing the set of possible contact configurations for the basic contact.

For states with only one basic contact DCr is equal to this set. For states with more than one basic contact DCr is obtained as the intersection of the sets of possible contact configurations of the involved basic contacts. The domains DC are computed in the same way, just including the uncertainty of the configuration sensor (i.e. the robot itself). Nevertheless, in order to on-line verify if a given sensed configuration belongs to the domain DC of a state with more than one basic contact, it is not necessary to explicitly compute DC. The verification can be done just by testing if the sensed configuration belongs to the sets of possible contact configurations of all the basic contacts involved. As an example, figure 4b shows the domain DC_6 of E_6 (basic contacts 1 and 2), obtained as the intersection of the domains DC_1 and DC_2 for the block orientation of figure 4a.

5.2 Force domains

The domains DGr are determined by using the dual representation of forces [4] that maps a generalized force $[f_x \; f_y \; \tau]$ into a point $[f_y/\tau \; -f_x/\tau]$ representing the force direction and a sign, $\text{sign}(\tau)$ representing the force sense. Since the module of the reaction force is not relevant for the state estimation, it does not matter if it is not considered in the dual representation. Therefore, generalized forces are represented by signed points in a dual plane. From now on, the dual representation of a domain DGr will also be indicated by DGr when the meaning is clear.

For each basic contact, the possible reaction forces must satisfy two conditions:

- *Contact-point condition*: the line of force must intersect the region where the contact vertex (or edge) can lie due to uncertainty. The set of dual points representing the forces that satisfy this condition will be called cc.
- *Direction condition*: the reaction force direction must lie inside the friction cone enlarged with the orientation uncertainty of the contact edge in the force reference frame. The set of dual points representing the forces inside this enlarged cone will be called dc.

The domain DGr of a state with only one basic contact is obtained as the intersection of cc and dc. As an example, figures 4c and 4d show the regions cc and dc for states E_1 and E_2 respectively, both for the block orientation of figure 4a, and figure 4e shows the resulting domains DGr_1 and DGr_2.

The domain DGr of a state with more than one basic contact is equivalent to the linear combination, with positive coefficients, of the possible compatible forces at each basic contact involved. As an example, figure 4f shows the domain DGr_6 of E_6, obtained as a linear combination of the domains DGr_1 and DGr_2 shown in figure 4e.

When the dual representation of the domains DGr of two one-contact states have different sign and overlap, the domain DGr of the corresponding two-contact state spans all the dual plane, indicating that any reaction force can be expected in that contact situation.

The uncertainty parallelepiped of the force measurement is not explicitly added to DGr in order to obtain DG. Instead, it is taken into account during the state estimation procedure to determine if a measured force is compatible with some state: the dual representation of the parallelepiped boundary is computed and if its intersection with the domain DGr of a state E is non-empty, the measured generalized force is considered to be compatible with E. For instance, picture C-3 in figure 5 shows the dual representation of the measured force (the center of the small circle) and of the vertices of the force uncertainty parallelepiped; in this case, the intersection with DGr_5 is non-empty and therefore the measured force is compatible with E_5.

5.3 Samples of current state estimation

Figure 5 shows situations in the physical space (column A), the configuration space (column B), and the dual force space (column C) for E_3, E_4 and E_5. The center of the small circles in column B indicates the current sensed configuration, and the center of the small circles in column C indicates the dual representation of the sensed generalized force.

The contact situation of picture A-1 can be identified as state E_3 using only configuration information, because the sensed configuration only belongs to DC_3. The same occurs with E_4 in the situation described in row 2.

The state corresponding to the contact situation of picture A-3 cannot be identified using only configuration information, because the sensed configuration is compatible with DC_1, DC_4 and DC_5 and therefore E_1, E_4 and E_5 are candidates. However, the sensed reaction force (picture C-3) is compatible with DGr_5 but not with DGr_4 (picture C-2)[2] or DGr_1 (not drawn), making it possible to estimate E_5 as the actual state. It must be noted that E_5 in picture A-3 could have the sensed generalized reaction force shown in picture C-2 which would be also compatible with DGr_4. If this was the case, it would be impossible to identify the current state with certainty using only current sensory data.

6 Conclusions

The use of sensory information on configuration and generalized reaction force for a specific fine-motion planning approach has been described in the paper. During the off-line planning phase, the possible actual configuration and generalized reaction force domains of each task state are computed and used to determine the robot fine-motion movements of the plan. This computation takes into account both friction and geometric uncertainty. By adding sensory uncertainty, the possible observed configuration and generalized reaction force domains of each task state are also set up; these domains are used during the on-line plan execution in order to identify the current task state but they do not need to be explicitly built.

The software modules to automatically generate these domains for three degrees of freedom tasks (planar movements) have been implemented in 'C' language on a Silicon Graphics workstation (CRIMSON/ELAN). The configuration domains are parameterized in the robot orientation; thus, much of the geometric computation to classify sensory data is two-dimensional and the results are easily visualized. The running time to decide if a sensed configuration is compatible with a given task state ranges from 70 to 400 μs depending on the number of basic contacts involved in the state. The force domains are computed using the dual representation of forces. This allows a two-dimensional representation of generalized force directions, and operation between forces are reduced to relatively simple geometric computation. The running time to decide if a sensed generalized force is compatible with a given task state ranges from 50 to

[2] Since contact 4 is type 2 DGr_4 is invariant with ϕ_r [16].

300 μs also depending on the number of basic contacts involved in the state.

Nevertheless, there are contact situations that cannot be identified by using only current sensory information; then, some history about the previous task states, configurations and reaction forces is necessary. Some heuristics can be applied in these cases, but they are tailored for a specific planner and therefore are not general.

Generalized reaction force domains could cover almost all the force space when the mobile object has movement constraints or a small range (in the order of geometric uncertainty) in its degrees of freedom. In this case the configuration and force sensory information will not probably be enough to identify the task state, but at the same time the constraints could make the selection of a proper operator to go on with the assembly easier.

Finally, besides the analytical approach described in the paper, learning techniques to state classification are being studied as an efficient complementary method [12] [17] especially useful to help in ambiguous situations.

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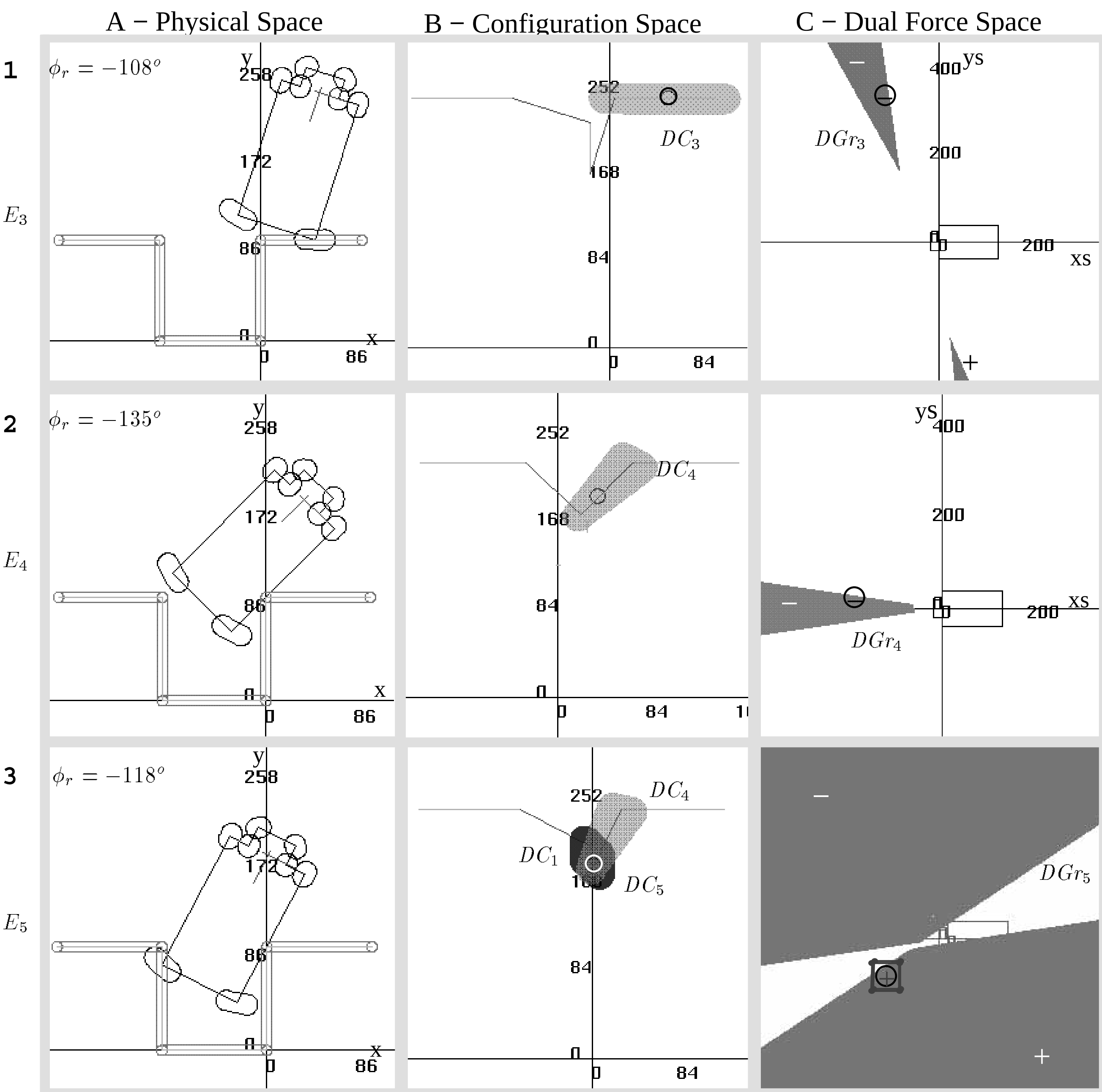

Figure 5: *Configuration and force domains for states* E_3, E_4 *and* E_5.