Leaving on a Plane Jet

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Abstract – *This is a continuation of our research on the Universal Planar Manipulator (UPM), a device capable of manipulating multiple generic objects (cans, chess pieces, poker chips, tools, etc.) with a single horizontally-vibrating, rigid plate (3 dofs). Objects are propelled by sliding frictional forces developed against the vibrating plate. A special plate vibration creates an average force field called the "jet" which is local, i.e., it is only non-zero near its center. By applying jets at different objects' locations in some succession, objects can be made to displace a small amount individually, enabling full parallel manipulation. In particular, a single object can leave on a plane jet, if the jet's center is made to track, and its direction made aligned with that object's motion. In this paper we provide visualization of the jet with respect to changes in its center, orientation, and focus parameters. Described also are two experiments showing the UPM as a tangible-user interface (docking a beer can to the user's hand) and as a chess player (executing moves of an endgame).*

1 Introduction

Planar manipulation is a fundamental feature in automation. Example applications include parts feeding, automated assembly, inspection, etc. Gripper-based manipulation is complex (arm and end-effector control) and often non-robust. This has motivated research on gripperless/non-prehensile methods for part manipulation. One inspiration is the bowl-feeder, which achieves robust parts feeding of parts as these interact passively with hard toolings. Because tooling design is hard and sensitive to part, workspace, and function changeover [2], one goal of research in this area is the design of a generic, software-configurable part manipulator. One step toward that end has been the work on flexible parts feeding [3].

Non-prehensile manipulation approaches so far researched include toppling [4], vibrations-induced entrapment [5], continuous force fields [6], "passive juggling" [7] an others. Another active research area is the design of mechanical hardware which can support those kinds of manipulation, which include arrays of micro- [8] and macro-actuators [9], and multi-dof rigid [10] and non-rigid [11] vibratory plates.

This is a continuation of our research on the Universal Planar Manipulator (UPM), a device capable of manipulating multiple objects with a single horizontally-vibrating, rigid plate (3 dofs). Our focus has been to design a non-prehensile programmable device with simple mechanics whose complexity does not scale with object count. Objects motion is induced by sliding frictional forces developed against the vibrating plate. This result is interesting since the plate moves along 3 degrees of freedom and a set of N objects has at least $2N$ dof's (e.g., when rotation is ignored).

Objects handled by the UPM need to rest on a flat face (i.e., be non-rolling), such as tools, books, beverage and pharmaceutical bottles, poker chips, chess pieces, etc.

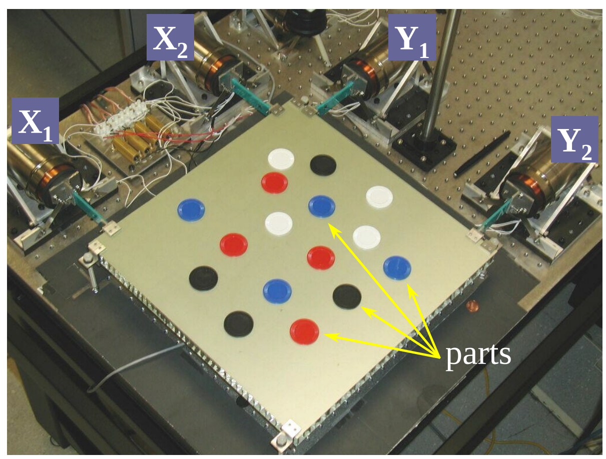

Figure 1: Manipulation via a supporting horizontally-vibrating surface: multiple objects are displaced via friction.

Previously [1], we've described a special plate vibration which produces an average frictional force field called a "jet". The jet is negligible everywhere but around a small neighborhood of the plate called the jet's center. Near the center, the jet field is oriented along a desired direction. With this primitive, a single object "can leave on a jet"[1],

[1] Pun with John Denver's song intended...

i.e., it can be displaced along a chosen direction while keeping all others still. This capability is non-obvious since all objects lie on the same rigid plate. By displacing individual objects a small amount in some succession (time-division multiplexing) we achieve many-object parallel manipulation.

In Figure 2, three objects are shown resting on a horizontal surface at positions P_1, P_2, P_3 (objects position's are recovered by sensing). A task (sorting, feedings, etc.) prescribes independent paths for each object, shown as the thick lines going through the objects' centers. By applying a jet at position P_i, the ith object can be displaced a small amount while keeping all others still. Parallel manipulation is realized by successively displacing each object a small amount d_1, d_2, and d_3 along its prescribed path (time-division multiplexing).

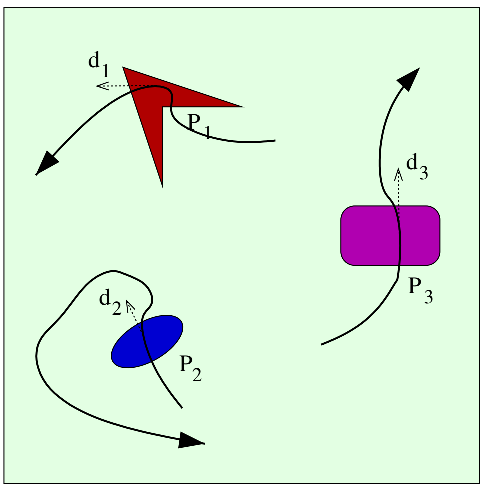

Figure 2: Illustration of parallel displacement of three objects along independent paths.

In this paper we present a visualization of the jet field with respect to variations in its focus, center, and orientation parameters. We also present two novel demonstrations of the UPM's programmable and parallel manipulation capabilities: (a) the UPM as a tangible-user interface: a beer can placed at a random location is displaced towards the user's hand, also placed over the UPM at an arbitrary location; (b) a chess player: the UPM chess endgame moves for six pieces lying simultaneously on its surface.

The remainder of this paper is organized as follows: In Section 2 we present visualizations of the jet as its intrinsic parameters are varied. In Section 3 we present two novel experiments with the UPM. Conclusions are presented in Section 4.

2 Leaving on a Jet

2.1 Review: the jet field

The jet, introduced in [1] is an average sliding friction force field computed over one period of a horizontal vibration of the rigid plate. Here we review it's building blocks.

Let $\mathbf{v}(\mathbf{P}, t)$ denote the instantaneous velocity at a point $\mathbf{P}$ on the plate's surface S. Consider a part (idealized to a point) of mass m lying at $\mathbf{P}$ on S. Assume the part's speed is negligible with respect to $\mathbf{v}(\mathbf{P}, t)$. Assume plate motion is such that friction is always of the *sliding* type.[2] A frictional force $\mathbf{f}(\mathbf{P}, t)$ of fixed value μmg in the direction of $\mathbf{v}(\mathbf{P}, t)$ is produced at point $\mathbf{P}$, where μ, g are the constant of sliding friction and the acceleration of gravity, respectively:

$$\mathbf{f}(\mathbf{P}, t) = \mu mg \frac{\mathbf{v}(\mathbf{P}, t)}{||\mathbf{v}(\mathbf{P}, t)||} \tag{1}$$

From the above, obtain the frictional force $\bar{\mathbf{f}}$ applied to the part *averaged* over the entire motion:

$$\bar{\mathbf{f}}(\mathbf{P}) = \frac{\mu mg}{T} \int_0^T \frac{\mathbf{v}(\mathbf{P}, t)}{||\mathbf{v}(\mathbf{P}, t)||} dt \tag{2}$$

The plate's rigid velocity $\mathbf{v}(\mathbf{P}, t)$ is chosen so the jet is *local*, i.e., it is negligible everywhere except in the neighborhood of its center C; specifically, it should be finite and oriented along a chosen direction $\hat{\mathbf{d}}$, and its magnitude should decay rapidly as one moves away from C. This is achieved by making $\mathbf{v}$ be the sum of two rigid velocities: (i) a translational feeding waveform $\mathbf{v}_{tr}$, oriented along $\hat{\mathbf{d}}$; (ii) a non-feeding sinusoidal rotation $\mathbf{v}_{rot}$, centered at C, and attenuated by a parameter ρ, namely [1]:

$$\begin{aligned} \mathbf{v}_{tr} &= \cos(t) - \frac{1}{2}\cos(2t) \\ \mathbf{v}_{rot} &= \sin(\frac{2}{3}t) \\ \mathbf{v}(\mathbf{P}, t) &= \mathbf{v}_{tr}\hat{\mathbf{d}} + \frac{2}{\rho}\mathbf{v}_{rot}(\mathbf{P} - \mathbf{C})^{\perp} \end{aligned} \tag{3}$$

The rational behind $\mathbf{v}(\mathbf{P}, t)$'s components is two-pronged: (1) Radial scaling: near C, $\mathbf{v}_{rot}$ vanishes and $\mathbf{v}_{tr}$ dominates. Because the latter is asymmetric [12], a part will feed there along $\hat{\mathbf{d}}$. Away from C, $\mathbf{v}_{rot}$ dominates; because it is symmetric, it creates no feeding forces. (2) Per-component annihilation: each of $\mathbf{v}_{tr}$'s c components are non-feeding with $\mathbf{v}_{rot}$. In [1], we derive two simple conditions which yield a non-feeding sum of two sinusoids: (a)

[2] This is possible since under the present motion, low relative acceleration seldom coincides with low relative velocity, generally accepted as the precondition for stiction.

when the frequencies are related as odd numbers; or (b) when the waveforms share a root. Expressing all frequencies as integer numbers we get 2 for $\mathbf{v}_{rot}$ and 3 and 6 for $\mathbf{v}_{tr}$'s components. 2 is non-feeding with 6 because they relate as $1:3$. 2 and 3 are potentially feeding, so we look at the originating components, $cos(t)$ and $sin(2t/3)$, which share a root and are therefore non-feeding. Note that while $\mathbf{v}_{rot}$ is non-feeding with either element of $\mathbf{v}_{tr}$, it is actually weakly feeding with their sum, due to non-linearities in the jet's computation. This is the reason the jet is not exactly zero everywhere.

2.2 The radius of action ρ

The ρ parameter controls $\mathbf{v}_{rot}$'s amplitude relative to $\mathbf{v}_{tr}$, Equation 3. Roughly at distance ρ from C, the two signals have equal amplitude, so this parameter controls the radius beyond which $\mathbf{v}_{rot}$ dominates over $\mathbf{v}_{tr}$. This effect is illustrated in Figure 3, for two values of ρ. Without loss of generality, consider an origin-centered jet oriented along $+\mathbf{y}$. Examining the field's values along the x and y axes, one notices those values have zero x components. This enables a convenient visualization of the jet's decaying strength along its forward (y in this case) and perpendicular (x in this case) directions. As shown in Figure 4, the jet decays rapidly along both cross sections, and more rapidly along the perpendicular one, where, in fact, small negative feeding forces (called *back feeding*) are found roughly ρ away from the origin. Back-feeding effects are more pronounced with other rotation signal candidates such as $\sin(t)$ and $\sin(2t)$, which reinforced $\sin(2t/3)$ as a good choice.

2.3 The center C and orientation $\hat{\mathbf{d}}$

A jet's center C can be positioned, and the jet's direction $\hat{\mathbf{d}}$ oriented arbitrarily in the plate's plane. If C is under and object of choice, the latter will be displaced virtually independently of any other object on the plate. Jets positioned at various plate locations and at different orientations are shown in Figure 5. Notice that because the jet is not properly zero away from its center, the round-robin parallel manipulation algorithm must account for drift occurring at off-center objects during the manipulation process (in practice, the correction is done automatically by computer vision).

3 Playing Chess

Two experiments with the UPM were described in [1]. Here we present two more, geared at (i) showing the device as a novel tangible user interface and (ii) demonstrating that the device can manipulate non-flat objects (unlike the poker chip and coins of previous demos).

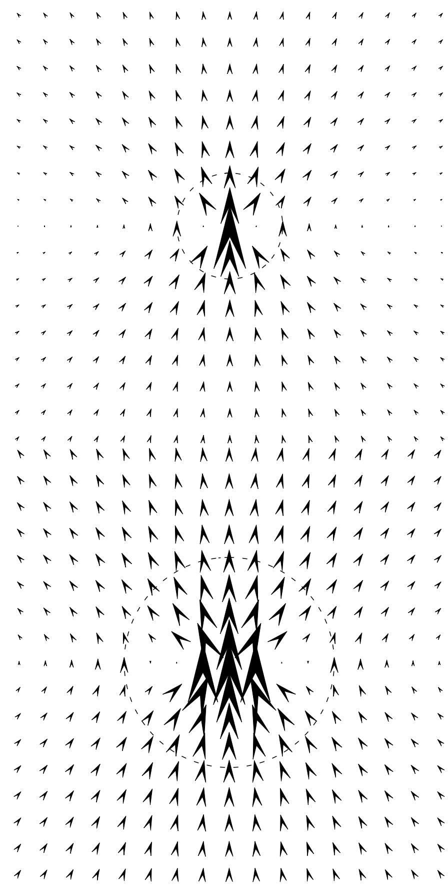

Figure 3: Varying the ρ parameter controls the jet's radius of action. The fields are plotted on the unit square. A circle of radius ρ is drawn on the origin. $\hat{\mathbf{d}} = (0,1)^{\perp}$. Top: $\rho = 0.25$. Bottom: $\rho = 0.5$.

3.1 Docking beer cans to a hand

This is a novel use of the UPM as a tangible user-interface for humans. The device is used as an entirely harmless and unobtrusive physical interface. A can of beer is placed on the UPM at an arbitrary location. A user places his hand somewhere on the plate as if about to grasp the can, but at a distance. Through computer vision, the UPM locates both the can and the user's requesting hand and displaces the former along a smooth spline so as to dock it into the latter. The user releases the can and replaces his hand elsewhere; the process repeats (the can docks again), as shown in Figure 6.

3.2 A chess endgame

A second experiment is presented demonstrating the UPM's use as a many-object manipulator. Six actual chess

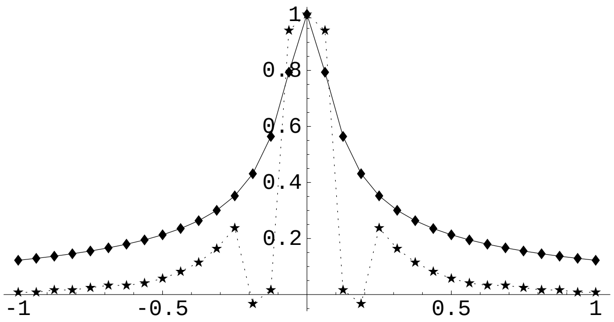

Figure 4: Normalized y-component of an origin-centered jet field oriented along $+\mathbf{y}$, plotted against distance from C, $\rho = 0.25$. Circles (resp. stars) are values measured along the y (resp. x) axis. Note the back-feeding (slight negative values) of feeding forces along x near $\pm\rho$ from the center.

pieces are displaced along pre-programmed motions of an actual chess endgame, show on the left of Figure 7. As shown in Figure 7, a wide metallic disk was glued to the bottom of each piece to increase stability under the UPM's vibration (very tall parts will tend to topple).

The UPM's plate is appropriately registered to a 64-square chess board. Pieces are initially scattered over the UPM at random locations. The device then brings them to their initial desired locations. It then proceeds to execute the moves, one by one.[3] As pieces are captured, they are simply driven out of the plate. Figure 8 shows snapshots of the experiment taken both from an overhead and an external camera. The overhead images shown registered with the chessboard are the ones used by the UPM to recover pieces' locations.

4 Conclusion

New visualization and experiments with the Universal Planar Manipulator (UPM) were described. Novel experiments were performed with the UPM showing potential application as a tangible interface and as a parallel manipulator for non-flat objects (chess pieces). Future work will involve refining the prototype's hardware to obtain closer to model plate motions, resulting in cleaner jets, and enhancements to computer vision aiming at more sophisticated interactive demonstrations.

[3]The device is unable to make knights "jump"...

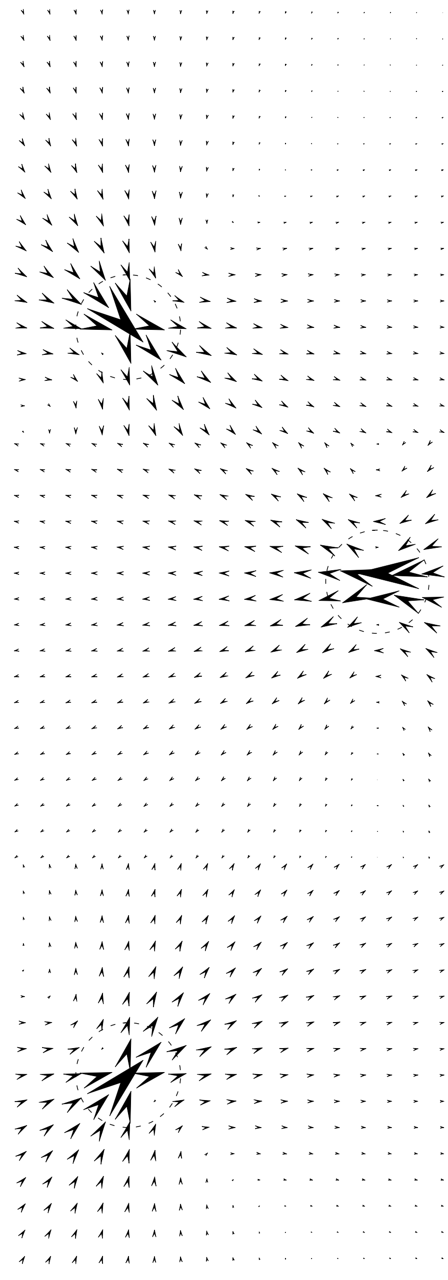

Figure 5: Three jets are shown drawn in the unit square, $\rho = 0.25$. From top to bottom, their centers are $(-0.5, -0.5)$, $(0.75, 1/3)$, and $(-0.5, 0)$, and their directions $(-1, -1)$, $(-1, 0)$, and $(1, 1)$, respectively. Circles of radius 0.25 are drawn dashed at each jet's center.

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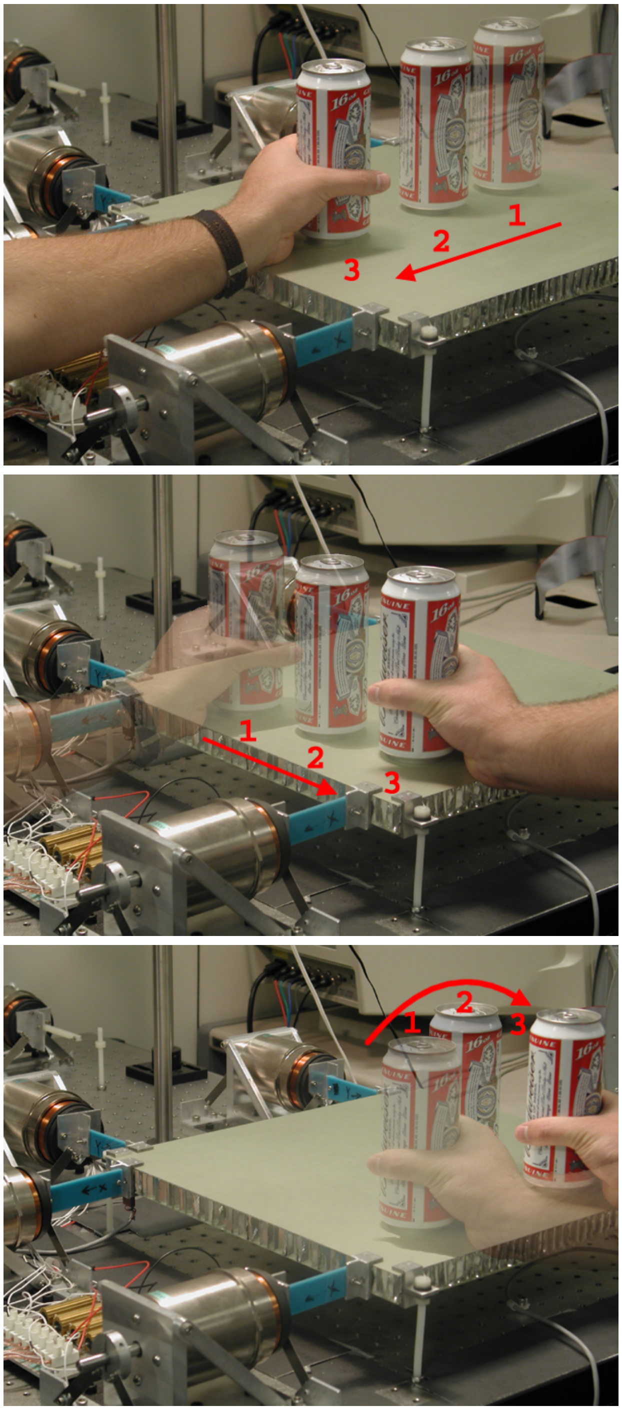

Figure 6: The beer can experiment. Three stop-motion frames are shown, each overlaying three consecutive can positions, labeled 1, 2, and 3, corresponding to can's initial, midstream, and final (docked) configuration. On the bottom picture the can has to move along a curve so as to dock correctly into the user's hand.

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1. ---  Kd6
2. Bxf5 Nc3+
3. Kc2  Kc6
4. Kxc3 Kd6
5. Kc4 Kc6
6. Ra6\# 1-0
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Figure 7: Left: list of endgame moves. Right: A chess piece adapted with a wide disk-shaped base to increase stability.

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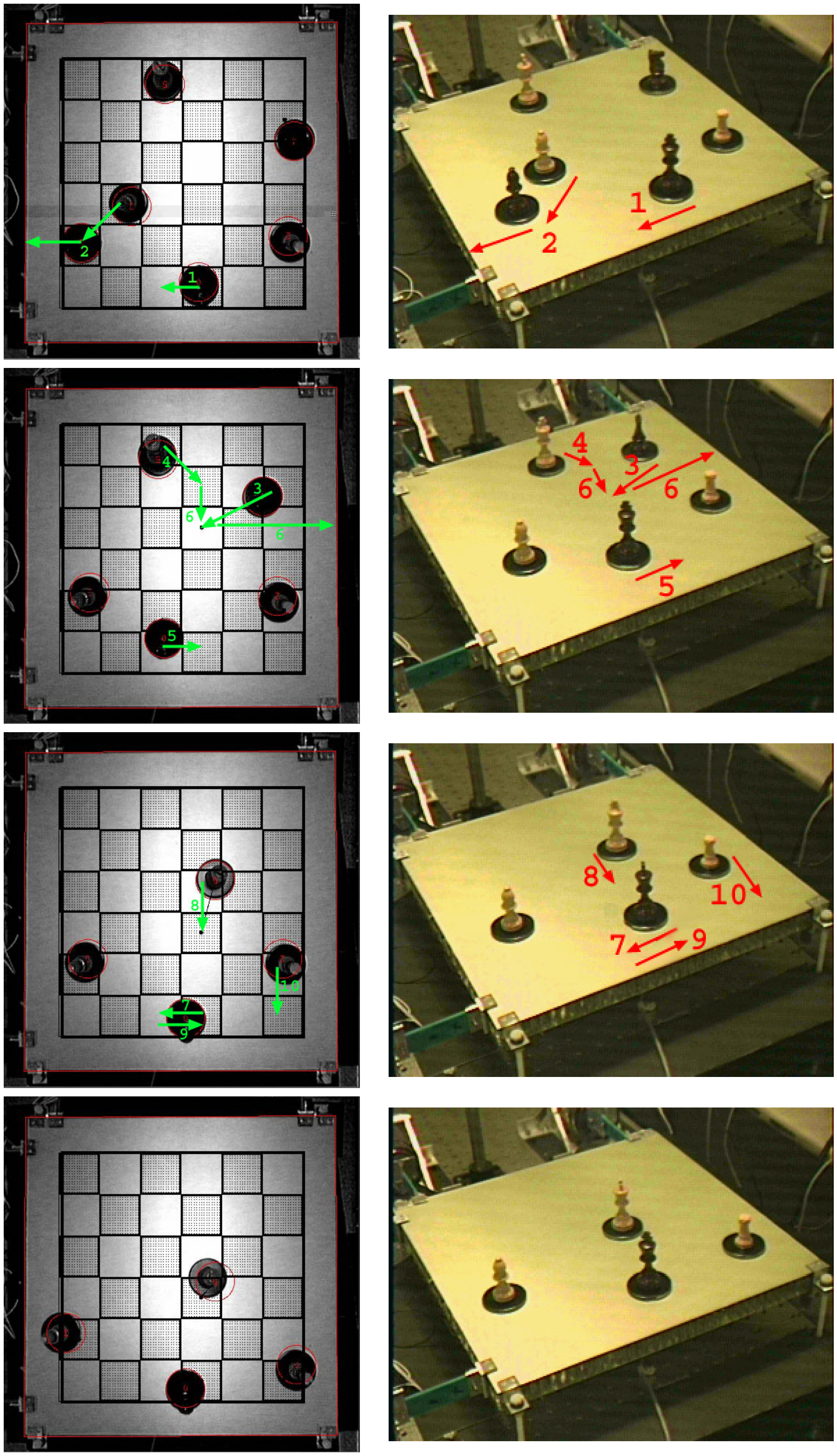

Figure 8: The chess experiment. The left (resp. right) column shows the overhead (resp. external) camera view. At every shot, the desired moves are labelled with green arrows and numbers which correspond to the endgame sequence in the text.