The Innovative Ceiling Robot

Timo Overboon, MSc.
Johan Smeets, MSc.
Dr. ir. Helm Jansen
Prof. dr. Elena Lomonova
Outline

• Background concept
• Magnetically suspended planar motor
• Contactless energy transfer system
• Prototype
• Measurement results
Research areas EPE group

- Actuators for high-tech mechatronics
- Motors and drives for automotive systems
- High-speed electrical machines
- Actuators for medical applications
- Multi-level and multi-port converters
- Wireless energy transmission
- Electromagnetic design & analysis tools
Magnetic levitation and propulsion

Levitated planar motor
*Flying carpet*
Based on repulsive force

Suspended planar motor
*Ceiling Robot*
Based on attractive force

Levitation
Suspension
Multiple movers for PCB assembly

Top view

Component feeder

Mover 1

Mover 2

Mover 3

Mover 4

PCB
Novel actuator concept for Pick & Place applications, including:

- Magnetic suspension
- Planar propulsion
- Fail-safe operation
- Contactless energy & data transfer
- Position detection
Magnetic suspension & propulsion

Magnetically suspended ceiling actuator
– Mover actuated underneath stator/ceiling
– Gravity compensation based on attractive force

Requirements
• Control in 6 degrees-of-freedom \((x, y, z, \psi, \theta, \phi)\)
• Long-stroke actuation in xy-plane
• Passive gravity compensation & fail-safety
  → Iron and permanent magnets
Checkerboard PM array for “unlimited” stroke in xy-plane

4 iron-cored linear motors
- Separately excited three-phase
- Rotated 45° wrt to PM array
- Propulsion force along x or y
- Passive normal force, $F_{z,r}$
Model single linear motor

Based on $dq$-decomposition 3 phase currents

- Small force ripples:
  \[ F_x = k_x I_q \]
  \[ F_y = 0 \]
  \[ F_z = F_{z,r} + k_z I_d \]

- Only considerable torque $T_y$ [1]:
  \[ T_y(x) = T_{y,r}(x) + k_d(x) I_d + k_q(x) I_q \]

Model ceiling robot

- Total sum of forces and torques:

\[ \overrightarrow{\omega} = \Gamma \overrightarrow{I} + \Gamma_0 \]

- Wrench vector:

\[ \overrightarrow{w} = [F_x \ F_y \ F_z \ T_x \ T_y \ T_z]^T \]

- Current vector:

\[ \overrightarrow{I} = [I_{d,1} \ I_{q,1} \ \ldots \ I_{d,4} \ I_{q,4}]^T \]

Force & torque decoupling

- Inverse model:

\[ \overrightarrow{I} = \Gamma^{-} (\overrightarrow{w}_{des} - \Gamma_0) \]

- \( \Gamma^{-} \): Moore-Penrose inverse for minimized losses
Goal: Minimized ohmic losses during acceleration ($a$)

$$P_{losses} = \frac{3R_{coil}}{2k^2} \left( (mg - 4F_{z,r})^2 + 4m^2a^2 + 4m^2a^2 \frac{r_z^2}{r_1^2 + r_2^2} \right)$$

- **Requirements:**
  - Peak acceleration: 7 m/s$^2$
  - Mass payload: 6 kg
- Optimization performed with 2D & 3D analytical models

### Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole pitch ($\tau_p$)</td>
<td>12 mm</td>
</tr>
<tr>
<td>Magnet height ($h_m$)</td>
<td>4.2 mm</td>
</tr>
<tr>
<td>Remanence ($B_{rem}$)</td>
<td>0.77 T</td>
</tr>
<tr>
<td>Airgap length ($h_g$)</td>
<td>3 mm</td>
</tr>
<tr>
<td>Stack length ($L_s$)</td>
<td>54 mm</td>
</tr>
<tr>
<td>Slot height ($h_s$)</td>
<td>12 mm</td>
</tr>
<tr>
<td>Slot pitch ($\tau_s$)</td>
<td>10.9 mm</td>
</tr>
<tr>
<td>Total mass ($m$)</td>
<td>12 kg</td>
</tr>
</tbody>
</table>
Magnetic loading

\[ P_{\text{losses}} = \frac{3R_{\text{coil}}}{2k^2} \left( (mg - 4F_{z,r})^2 + 4m^2a^2 + 4m^2a^2 \frac{r_z^2}{r_1^2 + r_2^2} \right) \]

- \( F_{z,r} \sim B^2 \) → magnetic loading limited
- \( k \sim B \) → motor constant low
- Magnet grade with low \( B_{\text{rem}} \) → plastic bonded magnets
- Large airgap length depends on acceleration → CET inside airgap

\[ (mg - 4F_{z,r}) = 0 \]

\[ k > \]

TU/e
Technische Universiteit Eindhoven
University of Technology
Contactless transfer of energy

Based on resonant inductive coupling
- Primary coils integrated in the airgap of the planar motor
- Secondary coil beside each linear motor on the mover

Requirements
- Average output power of 335W
- Low positional variation
- Integrated in the Ceiling Robot
Magnetic model: 3D Harmonic Modeling

Solution derived for 3D magnetic vector potential with Fourier series to model the inductance of the coils [1]

\[
\begin{bmatrix}
\frac{\partial^2 A_x}{\partial x^2} + \frac{\partial^2 A_x}{\partial y^2} + \frac{\partial^2 A_x}{\partial z^2} \\
\frac{\partial^2 A_y}{\partial x^2} + \frac{\partial^2 A_y}{\partial y^2} + \frac{\partial^2 A_y}{\partial z^2} \\
\frac{\partial^2 A_z}{\partial x^2} + \frac{\partial^2 A_z}{\partial y^2} + \frac{\partial^2 A_z}{\partial z^2}
\end{bmatrix}
\begin{bmatrix}
J_{\text{coil},x} \\
J_{\text{coil},y} \\
0
\end{bmatrix} = -\mu
\begin{bmatrix}
\sigma \frac{\partial A_x}{\partial t} \\
\sigma \frac{\partial A_y}{\partial t} \\
0
\end{bmatrix}
\]

Ability to include

- Coils and magnets
- Conducting and soft-magnetic materials
- Including eddy-current reaction field
- Slots and cavities

Electric model

Circuit model for multiple primary and a single secondary coil

Output secondary coils connected in series

\[
\begin{bmatrix}
V_{p1} \\
V_{p2} \\
\vdots \\
V_{pk} \\
V_s
\end{bmatrix} =
\begin{bmatrix}
Z_{p1p1} & Z_{p1p2} & \cdots & Z_{p1pk} & Z_{p1s} \\
Z_{p2p1} & Z_{p2p2} & \cdots & Z_{p2pk} & Z_{p2s} \\
\vdots & \vdots & \ddots & \vdots & \vdots \\
Z_{pkp1} & Z_{pkp2} & \cdots & Z_{pkpk} & Z_{pks} \\
Z_{sp1} & Z_{sp2} & \cdots & Z_{spk} & Z_{ss}
\end{bmatrix}
\begin{bmatrix}
I_{p1} \\
I_{p2} \\
\vdots \\
I_{pk} \\
I_s
\end{bmatrix}
\]
Position independent energy transfer

Constraints for a low variation in output power

• No salient ferromagnetic structures around the cores

• Transfer from sets of three of four secondary coils

• Single layer of primary coils for a maximal output power
Proposed structure

Primary coil array for “unlimited” stroke in xy-plane

- 4 air-cored secondary coils connected in series
- 3 primary coils activated per secondary coil
- Primary and secondary coil height limited to maximal 2 mm

Bottom view

Primary coils

Secondary coil
Final design

Specifications optimized design:
• planar stroke: 200x200 mm²
• nominal acceleration: 5 ms⁻²
• power transfer: 335 W
• variation power transfer: 15%
• Mover size: 37x37 cm²
• moving mass: 9 kg
6 DOF position control & planar tracking

1. Start up
Gap: 0 mm → 1.5 mm

2. Short stroke
Gap: 0.2 mm → 2.5 mm
Rotations: -5 mrad → +5 mrad

3. Long stroke
x and y: max 250 mm

Video
Conclusions

- Novel magnetically suspended planar motor underneath stator
- Passive gravity compensation for low power dissipation & fail-safety
- 6 DOF control and long-stroke movement with three-phase excitation
- Small tracking error

- Integrated design planar motor and CET system
- Energy transfer at every position of the mover
- Low variation in output power
Thank you

Come and see our prototype!
Booth #281