

A Low-Cost Fully 3D-Printed Automated Magnetic Bead Capture System with Real-Time Optical Monitoring

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Summary:

In this work we present a low-cost, 3D-printed magnetic bead-capturing system that uses an automatic magnet-retraction mechanism to control magnetic bead capture, and a (LDR) light-dependent resistors and LED (light-emitting-diode) based optical monitoring system integrated in a custom-made 3D printed microtube rack that was added to monitor real-time bead accumulation for up to eight microtubes simultaneously.

Keywords: 3D printing, paramagnetic beads, magnet-retraction mechanism, photoresistor, optical detection

Background, Motivation and Objective

Magnetic beads are widely used in biosensing, diagnostics, and sample preparation, and are typically separated from solution using magnetic racks or separators [1–4]. The magnetic bead-capturing step usually relies on manual visual inspection to determine whether the beads have fully migrated toward the magnet and whether the remaining liquid can be extracted. This manual reliance on the operator's judgment can make the process tedious when handling multiple samples with different bead concentrations, as the operator must repeatedly verify that all beads have been fully captured [5,6]. Even in automated sample-preparation systems, bead capture is typically controlled by a fixed, time-based protocol rather than real-time sensing [7]. Operators often need to adjust capture time manually because time-based methods do not account for variations in bead concentration, viscosity, or sample composition. To address this, we developed a low-cost, 3D-printed bead-capturing system that combines an automatic magnet-retraction mechanism with an LED–LDR sensing module for real-time monitoring of bead accumulation. This makes the system suitable for automated sample-preparation workflows.

Description of the New Method or System

The automatic bead-capturing system consists of two integrated modules: a magnet-retraction mechanism with eight permanent magnets and a custom 3D-printed rack for eight 2 mL microtubes. The mechanism actuates four linked arms, each carrying two magnets that move toward the tubes for bead capture or retract for

releasing the beads, the mechanism is driven by a single micro-servo motor. The microtube rack aligns with the mechanism and incorporates eight pairs of green LEDs and LDRs for optical sensing. The fully integrated system is shown in Fig. 1.

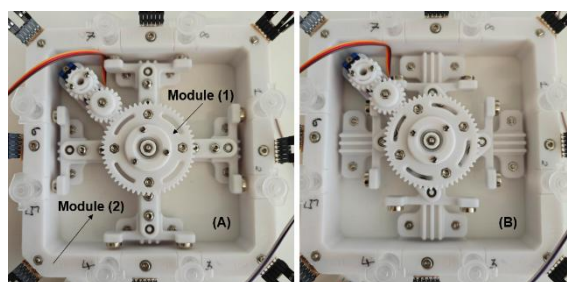


Fig. 1. 3D-printed setup of the integrated system showing Module 1 (permanent-magnet retraction mechanism) and Module 2 (LED–LDR optical detection system). In (A), the mechanism is fully extended, positioning the magnets close to the microtubes to capture the magnetic beads. In (B), the mechanism is retracted, moving the magnets away from the tubes to allow the beads to redisperse.

When a microtube containing suspended magnetic beads is placed in the rack, the beads initially remain dispersed and partially block the light, which increases the LDR's resistance. When the magnet-retraction mechanism is activated, the magnets move toward the microtubes and pull the beads to the microtube wall and clearing the optical path. This allows more LED light to reach the LDR, causing a sharp drop in resistance that indicates bead capture. (Fig.2) shows the alignment of the LEDs, LDRs, and microtubes inside the rack, ensuring the LED light passes through the tube before reaching the

sensor. This setup integrates magnet actuation with real-time optical sensing, forming what we believe is the first low-cost, 3D-printed platform combining an eight-magnet retraction mechanism with LED–LDR detection for automated bead accumulation. This enables feedback-controlled bead capture and improves the reliability of automated sample-preparation workflows.

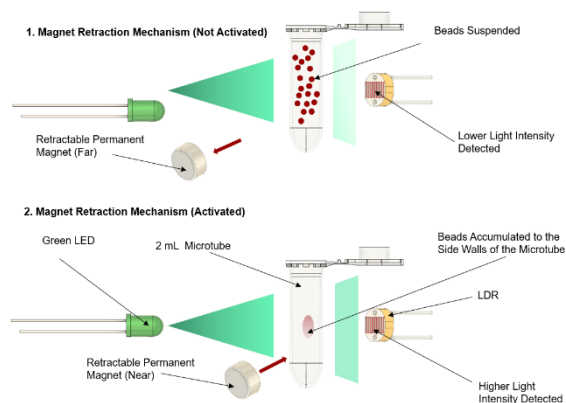


Fig. 2. Physical arrangement of the microtube, LED, and LDR inside the custom 3D-printed microtube rack. The proximity of the permanent magnet determines whether the beads accumulate along the tube wall (magnet near) or remain dispersed in the solution (magnet far).

Results

Magnetic beads were added in DI water to prepare six concentrations (2x, 1x, 0.5x, 0.25x, 0.125x, 0.0625x) using a 1:2 serial dilution, where 1x corresponded to 50 μ L of beads in 1 mL DI water. Two additional tubes were included: a DI-water baseline and a 2x reference. For the reference tube, the magnet was physically removed from the mechanism at that specific position so that this tube remained unaffected during the magnetic bead capture.

All eight tubes were placed in the custom microtube rack. The magnet actuation mechanism was initially in the retracted position (Fig. 1B) and then activated after a short delay. Each tube was measured five times. Between runs, bead-containing tubes including the 2x reference were manually shaken to redisperse the beads, while the baseline microtube remained undisturbed. Voltage signals from the LDRs were recorded at 10 Hz for 30 s as the beads migrated toward the magnet. For each microtube, the five voltage–time curves were averaged to obtain a representative response. The baseline produced a low, nearly horizontal signal (0–0.3 V), while the 2x reference produced the highest and similarly stable signal (3.5–4.0 V). The six bead concentrations produced averaged curves between these two extremes, with higher concentrations showing greater initial optical blockage and faster signal decay after magnet activation.

Although individual runs occasionally showed some irregularities between the 1x and 2x samples at early time points which might need further investigation. However, the averaged curves preserved the expected concentration-dependent trend. The resulting eight averaged curves are shown in Fig. 3.

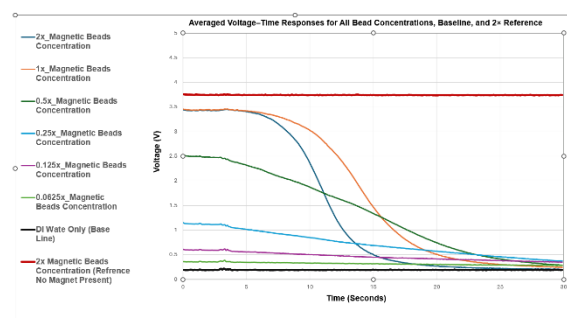


Fig. 3. Averaged voltage–time curves for six bead concentrations, the baseline, and the 2x reference. Each curve represents the average of five measurements, with the 2x reference measured without magnetic capture.

References

- [1] Paleček, E.; Fojta, M. Magnetic beads as versatile tools for electrochemical DNA and protein biosensing. *Talanta*. Elsevier December 15, 2007, pp 276–290. doi:10.1016/j.talanta.2007.08.020.
- [2] Aytur, T.; Foley, J.; Anwar, M.; Boser, B.; Harris, E.; Beatty, P. R. A novel magnetic bead bioassay platform using a microchip-based sensor for infectious disease diagnosis. *Journal of Immunological Methods* **2006**, 314(1–2), 21–29. doi:10.1016/j.jim.2006.05.006.
- [3] Guckenberger, D. J.; Pezzi, H. M.; Regier, M. C.; Berry, S. M.; Fawcett, K.; Barrett, K.; et al. Magnetic System for Automated Manipulation of Paramagnetic Particles. *Analytical Chemistry* **2016**, 88(20), 9902–9907. doi:10.1021/acs.analchem.6b02257.
- [4] Gijs, M. A. M. Magnetic bead handling on-chip: New opportunities for analytical applications. *Microfluidics and Nanofluidics*. November 2004, pp 22–40. doi:10.1007/s10404-004-0010-y.
- [5] Safarik, I.; Safarikova, M. Magnetic techniques for the isolation and purification of proteins and peptides. *BioMagnetic Research and Technology*. November 26, 2004. doi:10.1186/1477-044X-2-7.
- [6] Bu, M.; Christensen, T. B.; Smistrup, K.; Wolff, A.; Hansen, M. F. Characterization of a microfluidic magnetic bead separator for high-throughput applications. *Sensors and Actuators, A: Physical* **2008**, 145–146(1–2), 430–436. doi:10.1016/j.sna.2007.12.014.
- [7] Berensmeier, S. Magnetic particles for the separation and purification of nucleic acids. *Applied Microbiology and Biotechnology*. December 2006, pp 495–504. doi:10.1007/s00253-006-0675-0.