Supplementary Information

Analytical analysis

According to a previous analytical analysis (Han KH & Frazier AB, 2004, J Appl Phys 96: 5797-5802), the magnetic potential $V$ around a circular ferromagnetic wire (Fig. S1) can be expressed as:

$$V = -r \frac{2\mu_B}{\mu_w + \mu_B} H_0 \cos \phi, \quad r < a$$  \hspace{1cm} (S1)

$$V = -r H_0 \cos \phi + \frac{1}{r} k a^2 H_0 \cos \phi, \quad r > a \quad \left( k = \frac{\mu_w - \mu_B}{\mu_w + \mu_B} \right)$$  \hspace{1cm} (S2)

where $r$ and $\phi$ represent the cylindrical coordinate of the distance and angle, respectively; $\mu_B$ and $\mu_W$ are the permeabilities of the buffer solution and the ferromagnetic wire, respectively; $H_0$ is the external magnetic field; and $a$ is the effective radius of the ferromagnetic wire. Then, the magnetic field $\vec{H}_B$ around the wire can be expressed as:

$$\vec{H}_B = -\nabla V = -\frac{\partial V}{\partial r} \vec{a}_r - \frac{1}{r} \frac{\partial V}{\partial \phi} \vec{a}_\phi$$

$$= \left( H_0 \cos \phi + \frac{1}{r^2} k a^2 H_0 \cos \phi \right) \vec{a}_r + \left( -H_0 \sin \phi + \frac{1}{r^2} k a^2 H_0 \sin \phi \right) \vec{a}_\phi, \quad r > a$$  \hspace{1cm} (S3)
where $\vec{H}_B$ represents the magnetic field in the buffer solution around the wire and $\vec{a}_r$ and $\vec{a}_\phi$ are unit vectors for the $r$- and $\phi$-direction in the cylindrical coordinate, respectively.

By substituting $\cos \phi = \frac{x}{r}$, $\sin \phi = \frac{z}{r}$ and $r = \sqrt{x^2 + z^2}$ into Eq. (S3), the magnetic field $\vec{H}_B$ can be expressed as:

$$\vec{H}_B = \left[ H_0 + \frac{ka^2 H_0 (x^2 - z^2)}{\left(x^2 + z^2\right)^2} \right] \vec{a}_x + \frac{2xka^2 H_0}{\left(x^2 + z^2\right)^2} \vec{a}_z, \quad (S4)$$

where $x$ and $z$ represent the Cartesian coordinate and $\vec{a}_x$ and $\vec{a}_z$ are unit vectors for the $x$- and $z$-direction in the Cartesian coordinate, respectively. When $\chi_p |\vec{H}_B| > M_{PS}$, the magnetic force $\vec{F}_m$ on the beads is:

$$\vec{F}_m = \mu_B V_p M_{PS} \nabla |\vec{H}_B|, \quad (S5)$$

where $\chi_p$ represents the susceptibility of the magnetic beads, $V_p$ is the volume of the magnetic beads, and $M_{PS}$ is the saturation magnetization of the beads. The susceptibility $\chi_p$ and the saturation magnetization $M_{PS}$ of the magnetic beads used for analytical and numerical simulations are 0.192 and 30 kA/m, respectively. According to Eq. (S5), the $x$- and $z$-directional magnetic
forces (Fig. S2) on a magnetic bead can be rewritten as:

$$F_{mx} = \mu_B V_p M_{PS} \frac{\partial |\vec{H}_B|}{\partial x}, \text{ and} \quad (S6)$$

$$F_{mz} = \mu_B V_p M_{PS} \frac{\partial |\vec{H}_B|}{\partial z}. \quad (S7)$$

Then, the $x$- and $z$-directional magnetic forces on a magnetic bead are

$$F_{mx} = -\frac{2V_p M_{PS} x ka^2 B_0}{(x^2 + z^2)^2 \sqrt{(x^2 + z^2)^2 + 2ka^2(x^2 - z^2)}} \left( x^2 - 3z^2 + ka^2 \right), \text{ and} \quad (S8)$$

$$F_{mz} = -\frac{2V_p M_{PS} z ka^2 B_0}{(x^2 + z^2)^2 \sqrt{(x^2 + z^2)^2 + 2ka^2(x^2 - z^2)}} \left( 3x^2 - z^2 + ka^2 \right). \quad (S9)$$
Fig. S1  Cylindrical coordinates of a magnetic bead with respect to a circular ferromagnetic wire in a uniform external magnetic field, \( H_0 \).

Fig. S2  Direction of the magnetic force on a magnetic bead located around a circular ferromagnetic wire in a uniform external magnetic field, \( H_0 \).
Analytical and numerical simulations for the \( z \)-directional magnetic force

**Fig. S3** Analytical and numerical values for the \( z \)-directional magnetic force for varying levitation heights \( z \) of a magnetic bead. The hatched square in the inset represents the cross-section of the square ferromagnetic wire, taken perpendicular to the \( x \)-axis in Figure 1A.
Comparison of the analysis times for a standard RT-PCR method and for the proposed high-speed RT-PCR method

**Fig. S4** Process times obtained using a standard RT-PCR method and using the proposed high-speed RT-PCR method for diagnosing blood borne disease. The information on the left of the flow chart provides some general process times for the various methodologies executed with a sample. On the right, we present the process times of the proposed high-speed RT-PCR method.