High precision laser cleaning on the microscale using deep learning

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Laser cleaning is widely used in industrial manufacturing to remove contaminants such as paint, rust, and other surface impurities [1-3] from surfaces. Conventional methods, including chemical treatments, abrasive blasting, and other invasive techniques, often pose risks to substrates, potentially causing damage and offering limited accuracy. In contrast, laser cleaning provides better accuracy in removing contaminants from surface. However, it may also lead to excessive material removal ("over-machining"), which increases energy consumption and can inadvertently alter the surface properties of substrates. There is therefore great interest in integrating real-time feedback control into the laser cleaning process to optimise contaminants removal while preserving surface integrity.

Deep learning has recently gained widespread traction across various scientific disciplines due to its ability to solve complex problems directly from experimental data. This trend is also evident in laser materials processing [4], where advances have been made in areas such as parameter optimization [5, 6], real-time control and error correction [7], and real-time predictive visualisation [8]. Leveraging data-driven approach such as deep learning offers a promising avenue for addressing many of the challenges inherent in laser cleaning.

In this work, we demonstrated a real-time, neural-network-driven monitoring and controlling system to optimise the laser removal of 15 μm diameter polystyrene spheres from a glass substrate using femtosecond pulses. The substrate, placed on a 3D translation stage, was controlled autonomously, with the system making real-time decisions on pulse energy to minimise the number of laser pulses required for effective removal. This approach significantly enhanced photon efficiency and reduced the risk of surface damage. The demonstrated approach shows strong potential for enabling precise, non-damaging, and photon-efficient microscale laser cleaning in real time. It is particularly suited for high-precision industries, such as aerospace, electronics, and medical device manufacturing, where selective and precise material removal is critical.

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