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RESEARCH ARTICLE

Target Aiming Point Focusing Strategy for Destroying a Short-Range Target Using Distributed Laser Systems

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ABSTRACT Consider a scenario where multiple high power laser weapon systems are positioned closed to a base, in order to protect the base from an aerial target, such as a missile. We consider destroying a short-range flying target which is sufficiently close to the base. Using multiple lasers can reduce thermal blooming, which decreases the effective power that can be delivered to a target site in the atmosphere. Thus, this paper proposes utilizing multiple high power laser sources to aim on a single point of the target to maximize the attack efficiency and avoid directional disturbances. Once a target is detected by a search radar system, then the position of the target can be calculated in global coordinate systems and is shared by all laser systems through fiber-based wired links. Then, each laser aims at the target followed by firing at the target. This paper presents how to make multiple high power lasers aim at a single target point for maximizing the attack efficiency. Considering the case where there are more than one high power laser sources, this paper is novel in addressing the control and synchronization of every laser system. MATLAB simulations are used to verify the effectiveness of the proposed multi-laser systems.

INDEX TERMS Laser, distributed laser, precision control, high power laser.

I. INTRODUCTION

High power lasers are applicable on numerous fields such as laser machining [1], space science [2], and military application [3], [4]. Thanks to the development of high power laser system, such as chemical laser, high power laser of kW level has been realized [5], [6], [7], [8], [9]. Chemical lasers are somewhat bulky as they require a large amount of chemical storage and cooling system for its proper functioning [10].

Recently, laser weapon systems have been deployed to shoot down drones or small boats [11]. The laser can burn out sensors or motors, and detonate explosive materials. However, due to the power limit, a single laser weapon may have difficulty in destroying an aerial target, such as an incoming missile, with reflective layers. This inspired us to develop distributed laser weapon systems for protection against an incoming target.

This paper addresses using multiple high power laser weapon systems in order to protect a base. Consider a scenario where multiple high power laser weapon systems are positioned closed to the base, in order to protect the base from an incoming aerial target, such as a missile. One considers destroying a short-range target which is sufficiently close to the base. This scenario is relevant in anti-missile defense system, as in [6], [7], and [12].

Nowadays, most of the recent high power laser weapon system uses only a single laser source, as it is much convenient to combine numbers of lasers and match their phases. However, using multiple high power laser systems has advantages in anti-missile defense scenario. Using multiple lasers can reduce "thermal blooming", which decreases the effective power that can be delivered to a target site in the atmosphere [6]. Generating multiple radiant energy beams from separate laser sources to focus on the same site on a hostile missile reduces the missile destruction time [6].

As a single high power laser has only a single path to the target, the efficiency of the laser heavily depends on weather

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environment, obstacle, and the directional defense system of the target [13], [14]. In addition, if a reflective obstacle blocks the Line-of-Sight (LOS) between the target and a high power laser system, then the efficiency of the laser power will be extremely degraded. Moreover, specific area, such as head, of the target may be covered with hard materials for protecting against extreme heat.

Our paper shows that using multiple lasers, one can handle the case where obstacles block the LOS path to the target, or the case where the target has a defense system in a specific direction or for a specific region. It is desirable to utilize multiple high power laser sources to aim on a single target point to maximize the attack efficiency and avoid directional disturbances. This paper proposes using multiple high power laser sources to aim at a single point of a short-range target to maximize the attack efficiency.

Note that it takes some time to set the aiming direction of each laser toward a single target. In the case where the target information is not shared by all lasers, it is not trivial to make all lasers aim at the identical target point. In this paper, search radar systems are used for deriving the target's global position information. The target information is then shared by all lasers using fiber-based wired links, so that all lasers aim at the identical target point. This paper addresses how to make every laser aim at a single target point with the maximum allowable speed. The re-aiming control method is further proposed to compensate for the detection error of multiple lasers.

As far as we know, no paper in the literature handled precise control of multiple laser sources, as in our paper. Considering the case where there are more than one high power laser sources, our paper is novel in addressing the control and synchronization of every laser system.

Consider a scenario where multiple high power laser systems are positioned to destroy a target. Each high power laser system can communicate with other laser systems in real time using communication link. One can use fiber-based wired links for communication between the laser systems. Since the communication is done with the speed of light, it is assumed that the communication delay can be ignored. MATLAB simulations are used to verify the effectiveness of the proposed multi-laser systems.

To the best of our knowledge, this paper is novel in following aspects.

1) This paper proposes utilizing multiple high power laser sources to aim on a single point of the target to maximize the attack efficiency and avoid directional disturbances.
2) This paper addresses how to make every laser aim at a single target point with the maximum allowable speed.
3) The re-aiming control method is proposed to compensate for the detection error of multiple high power lasers.

The paper is organized as follows. Section II introduces the main results of this paper. Section III presents MATLAB simulations to verify the effectiveness of the proposed multi-laser systems. Section IV provides the conclusions.

II. LASER SYSTEM CONTROL

A. DEFINITIONS AND ASSUMPTIONS

Consider a military scenario where multiple high power laser weapon systems are positioned closed to a base, in order to protect the base from an incoming aerial target, such as a missile.

Suppose that there are M high power laser systems in total. p_i is the i-th laser system, where $i \in \{1, 2, \ldots, M\}$. Each p_i is equipped with high power laser source to aim at the target. Let $p_i = (x_i, y_i, z_i)^T \in \mathcal{R}^3$ denote the 3D global position of i-th laser system.

We say that a target is a *short-range* target once the relative distance between the target and every laser p_i ($\forall i \in \{1, 2, \ldots, M\}$) is less than a certain threshold, say β.

This paper uses the assumption, called the *short-range assumption*, as follows: *A short-range target is a target such that as a laser source aims at one point of the target, the point is observable using image sensors, such as thermal cameras.*

Note that as the distance between a target and a laser source increases, the short-range assumption may not be met. Suppose that a laser source aims at one point of a target which is too far from the laser source. The point may not be detectable using image sensors, due to the hardware limit of the image sensors or bad weather conditions.

This paper only considers a short-range target satisfying the short-range assumption. The threshold β for a short-range target is determined so that the short-range assumption is satisfied. This implies that β depends on the hardware limit of the image sensors as well as the weather condition. In MATLAB simulations, we thus consider the case where $\beta = 2$ km.

For instance, consider a target which is located at 2 km away from a deuterium fluoride chemical laser with output power of 2MW. Considering atmospheric transmission of 50 percents, the laser beam has 1.5 m as the beam size at the target [5]. As long as this beam size is detectable using high-resolution image sensors, $\beta = 2$ km is feasible.

It is desirable that we have large β if possible. However, β depends on the available laser technology. Target detection, discrimination and tracking over distances of several hundred kilometers are challenging. For example, in order to point the laser beam at a certain aim point with an accuracy of half a meter over a distance of 400 km, the angular pointing accuracy of the steering mirror has to be in the order of 10^6 radians [7]. Interestingly, [7] assumed that these challenges can be overcome in practice.

Let $\phi_i(k)$ denote the yaw angle of the aiming direction of laser p_i at time step k. Let $\theta_i(k)$ denote the pitch angle of the aiming direction of laser p_i at time step k. The angles $\phi_i(k)$ and $\theta_i(k)$ are depicted in Fig. 1. See that $\phi_i(k)$ is measured from the x-axis and that $\theta_i(k)$ is measured from the z-axis.

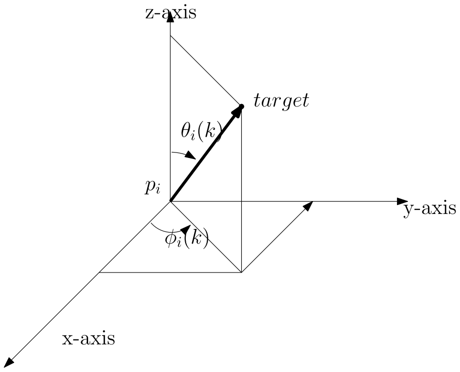

FIGURE 1. **A laser system p_i aims at the target at time step k. The aiming direction of p_i is depicted with a bold arrow in this figure.**

See Fig. 1 for an illustration of the case where p_i aims at the target at time step k. p_i is located at the origin. The aiming direction of p_i is depicted with a bold arrow in this figure.

Let $\dot{\phi}_{max}$ denote the maximum yaw change rate of the aiming direction, considering the hardware limit of the mirror control motor. Also, let $\dot{\theta}_{max}$ denote the maximum pitch change rate of the aiming direction, considering the hardware limit of the mirror control motor. Let dt indicate the sampling interval for controlling the aiming direction of laser source.

Suppose p_i aims laser at a target. Using the track sensor linked to p_i, one calculates the distance to the target. Suppose that the pulse is emitted at time step k. By calculating the return time of the signal pulse, p_i can calculate the distance to the target. Let $\hat{Z}_i(k)$ denote the *aiming point* on the target, detected by laser p_i at time step k. Let $L_i(k)$ denote the calculated distance for convenience.

Using $L_i(k)$, $\theta_i(k)$, and $\phi_i(k)$, one can derive the global 3D coordinates of the point detected by p_i as

$$\hat{Z}_i(k) = p_i + L_i(k)q_i(k). \tag{1}$$

Here, $q_i(k) = [s(\theta_i(k))c(\phi_i(k)), s(\theta_i(k))s(\phi_i(k)), c(\theta_i(k))]$. Here, $s(*)$ indicates $\sin(*)$, and $c(*)$ indicates $\cos(*)$.

In (1), one assumes that $L_i(k)$, $\theta_i(k)$, and $\phi_i(k)$ can be calculated accurately. By calculating the return time of the signal pulse, one can calculate $L_i(k)$. Moreover, $\theta_i(k)$ and $\phi_i(k)$ can be measured with high accuracy.

Suppose that $p_1 \in \mathcal{R}^3$ is at the origin of the global coordinates system. The global 3D position of a laser system, $p_i \in \mathcal{R}^3$, can be measured in the case where each laser system uses Global Positioning Systems (GPS). However, in practice, GPS may not be available. In the case where GPS is not available, Section II-B addresses how to calibrate p_i using track sensor measurements.

B. POSITION CALIBRATION OF EACH LASER SYSTEM

Suppose that $p_1 \in \mathcal{R}^3$ is at the origin of the global coordinates system. In order to calibrate $p_i \in \mathcal{R}^3$ using laser measurements, one sets a static test target, such that the relative distance between the target and every laser p_i ($\forall i \in \{1, 2, \ldots, M\}$) is less than β. In other words, the test target is a short-range target.

Suppose p_1 aims laser at the test target. Since the target is a short-range target, the point on the test target can be detected by all other lasers. Thereafter, all other lasers are controlled to aim at the identical point. Using (1), $\hat{Z}_1(k) = \hat{Z}_i(k)$ for all $i \in \{1, 2, \ldots, M\}$. In other words, one gets

$$\hat{Z}_1(k) = p_i + L_i(k)q_i(k). \tag{2}$$

Using (1) and (2), one further gets

$$p_i = p_1 + L_1(k)q_1(k) - L_i(k)q_i(k). \tag{3}$$

In this way, one can calculate $p_i \in \mathcal{R}^3$ ($\forall i \in \{1, 2, \ldots, M\}$) accurately.

C. CONTROL OF MULTI-LASER SYSTEMS WITH THE MAXIMUM ALLOWABLE SPEED

Note that it takes some time to set the aiming direction of each laser toward the aerial target. Search radar systems derive the target's global position information, say $\hat{Z}_g(k)$. The target information $\hat{Z}_g(k)$ is then shared by all laser systems through fiber-based wired links, so that every high power laser can also aim at $\hat{Z}_g(k)$ with the maximum allowable speed. One addresses how to make every laser aim at $\hat{Z}_g(k)$ with the maximum allowable speed.

1) AIM AT THE AERIAL TARGET

The target information $\hat{Z}_g(k)$ is shared by all laser systems, so that every high power laser can also aim at $\hat{Z}_g(k)$ with the maximum allowable speed. One next presents how to control the aiming direction of each laser p_i toward $\hat{Z}_g(k)$. The yaw angle of $\hat{Z}_g(k)$ with respect to p_i is

$$\phi_i^Z(k) = atan2(r[2], r[1]) \tag{4}$$

where $r = \hat{Z}_g(k) - p_i$, and $r[m]$ denotes the m-th element in r. In (4), $atan2(y, x)$ is the argument (also called phase or angle) of the complex number $x + j * y$.

At each time step n, one controls the yaw of i-th laser source with the maximum allowable speed, so that it converges to $\phi_i^Z(k)$. Let $e_\phi = \phi_i(n) - \phi_i^Z(k)$ indicate the yaw error for convenience. We then change e_ϕ so that it exists between $-\pi$ and π. We use

$$e_{\phi_2} = atan2(\sin(e_\phi), \cos(e_\phi)). \tag{5}$$

If $\|e_{\phi_2}\| > \dot{\phi}_{max} * dt$, then one controls the yaw of i-th laser source with the maximum speed $\dot{\phi}_{max}$ as follows.

$$\phi_i(n+1) = \phi_i(n) + sign(e_{\phi_2}) * \dot{\phi}_{max} * dt. \tag{6}$$

Here, $sign(e_{\phi_2})$ denotes the sign of e_{ϕ_2}. Otherwise, one uses

$$\phi_i(n+1) = \phi_i^Z(k). \tag{7}$$

In this way, the yaw of i-th laser source converges to $\phi_i^Z(k)$ as fast as possible.

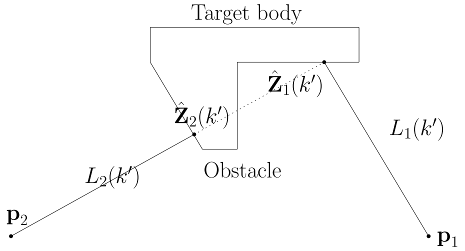

FIGURE 2. The LOS line between $\hat{Z}_1(k')$ and p_2 is blocked by obstacle body. In this case, $\|\hat{Z}_1(k') - \hat{Z}_2(k')\|$ is too large.

Next, one considers the pitch angle of the aiming direction of p_i. The pitch angle of the target $\hat{Z}_g(k)$ with respect to p_i is

$$\theta_i^Z(k) = atan2(\sqrt{r[1]^2 + r[2]^2}, r[3]) \tag{8}$$

where $r = \hat{Z}_g(k) - p_i$. Recall that $r[m]$ denotes the m-th element in r.

At each time step n, one controls the pitch of i-th laser source so that it converges to $\theta_i^Z(k)$ as fast as possible. Let $e_\theta = \theta_i(n) - \theta_i^Z(k)$ denote the pitch error for convenience. One then changes e_θ so that it exists between $-\pi$ and π. We use

$$e_{\theta_2} = atan2(\sin(e_\theta), \cos(e_\theta)). \tag{9}$$

If $\|e_{\theta_2}\| > \dot{\theta}_{max} * dt$, then one controls the pitch of i-th laser source with the maximum speed $\dot{\phi}_{max}$ as follows.

$$\theta_i(n+1) = \theta_i(n) + sign(e_{\theta_2}) * \dot{\theta}_{max} * dt. \tag{10}$$

Otherwise, one uses

$$\theta_i(n+1) = \theta_i^Z(k). \tag{11}$$

In this way, the pitch of i-th laser source converges to $\theta_i^Z(k)$ as fast as possible.

2) CHECK THE AIMING POINT

Once a laser of p_i aims with pitch angle $\theta_i^Z(k)$ and yaw angle $\phi_i^Z(k)$, then the track sensor linked to p_i emits a signal pulse towards the target. Suppose that the track sensor emits a signal pulse at time step k'. After calculating the return time of the signal pulse, p_i can calculate $\hat{Z}_i(k')$ based on (1). Recall that $\hat{Z}_i(k')$ presents the aiming point detected by p_i at time step k'.

Let $\zeta \approx 0$ denote a certain positive constant. If $\|\hat{Z}_j(k') - \hat{Z}_i(k')\| < \zeta$, then one says that laser p_j and laser p_i are *arranged* at the identical aiming point.

However, there may be a case where $\|\hat{Z}_j(k') - \hat{Z}_i(k')\|$ is too large. For instance, if a reflective obstacle blocks the LOS line between $\hat{Z}_j(k')$ and p_i, then $\|\hat{Z}_j(k') - \hat{Z}_i(k')\|$ may be too large, since a signal pulse cannot penetrate the obstacle. If $\|\hat{Z}_j(k') - \hat{Z}_i(k')\| > \zeta$, then one needs to reset the aiming point.

Fig. 2 illustrates the case where the LOS line between $\hat{Z}_1(k')$ and p_2 is blocked by obstacle body. In this case, $\|\hat{Z}_1(k') - \hat{Z}_2(k')\|$ is too large.

If $\|\hat{Z}_j(k') - \hat{Z}_i(k')\| > \zeta$ for any $i, j \leq M$, then one needs to set another aiming point. Among all aiming points measured by all lasers, one selects an aiming point which has the minimum height. In other words, one selects a detect point which is the lowest among all aiming points. Let *lowest aiming point* denote the selected aiming point. For instance, suppose that one use two lasers as plotted in Fig. 2. In this case, the lowest aiming point is $\hat{Z}_2(k')$, since it is lower than $\hat{Z}_1(k')$. In other words, $\hat{Z}_2(k')[3] < \hat{Z}_1(k')[3]$.

Suppose that p_1 aims at the lowest aiming point and a new signal pulse is emitted at time step k''. Then, p_1 can calculate the new aiming point $\hat{Z}_1(k'')$ using (1). Here, $\hat{Z}_1(k'')$ is the point detected by p_1 at time step k''.

The newly aiming point $\hat{Z}_1(k'')$ is shared by all laser systems through fiber-based wired links, so that every laser can also aim at $\hat{Z}_1(k'')$. The process repeats until all lasers are arranged at the identical aiming point. In this way, one can make all lasers focus on the lowest aiming point.

3) RE-AIM AT THE AIMING POINT

Suppose that at time step K, all high power lasers are arranged at the identical aiming point. Let $\hat{Z}_i(K)$ denote the target's point detected by p_i at time step K.

Even in the case where all high power lasers are arranged at the identical aiming point, measurement noise can still exist. Thus, it may not be feasible that $\|\hat{Z}_j(K) - \hat{Z}_i(K)\| = 0$ for all $i, j \leq M$. Once all high power lasers are arranged at the identical aiming point, then we have

$$\|\hat{Z}_j(K) - \hat{Z}_i(K)\| < \zeta, \tag{12}$$

for all $i, j \leq M$. Laser light must be delivered to a tight spot in order to be destructive. Algorithm 1 is used to make the laser beams super-imposed on the target point precisely. One next presents Algorithm 1 in detail.

Algorithm 1 slightly controls the yaw and pitch angle of p_i, so that the point detected by p_i and the point detected by p_1 are as close to each other as possible. In this algorithm, $\phi_i(K)$ is set as

$$\phi_i(K) = atan2(r_i[2], r_i[1]) \tag{13}$$

where $r_i = \hat{Z}_i(K) - p_i$, Also, $\theta_i(K)$ is set as

$$\theta_i(K) = atan2(\sqrt{r_i[1]^2 + r_i[2]^2}, r_i[3]) \tag{14}$$

Recall this paper assumes that the aiming point is visible using image sensors. In Algorithm 1, A_i presents the maximum perturbing for pitch and yaw change for p_i. Using (12), we derive A_i (in radians) as follows.

$$A_i = \frac{\lambda * \zeta}{\|p_i - \hat{Z}_i\|}. \tag{15}$$

Here, $\lambda \geq 1$ is a positive constant. (15) implies that as the relative distance between a laser and the target increases, A_i decreases. In MATLAB simulations, we use $\lambda = 3$.

Since the target is a short-range target, one has $\|p_i - \hat{Z}_i\| < \beta$ for all $i \in \{1, 2, \ldots, M\}$. Thus, (15) leads to

$$A_i > \frac{\lambda * \zeta}{\beta}. \tag{16}$$

In Algorithm 1, one keeps perturbing both the pitch and yaw angle of p_i in order to find the optimum aiming direction toward $\hat{Z}_1$. Let $minA$ represent the minimum perturbation angle of p_i. Here, $minA$ is determined by hardware information (e.g. motor specification in [15]) of p_i. It is desirable that $minA$ is as small as possible for accurate aiming process.

In simulations, one sets $minA = 0.01$ degree, which is feasible considering a high-resolution motor [15]. Consider a short-range target whose distance from a laser is 2 km. As one changes the aiming direction by 0.01 degree, the aiming point changes by $2000 * 0.01 * \frac{\pi}{180} \approx 0.3$ meter.

For precise control under Algorithm 1, the practical requirement for $minA$ is as follows.

$$A_i \gg minA. \tag{17}$$

Using (16) and (17), it is desirable that

$$\frac{\lambda * \zeta}{\beta} \gg minA. \tag{18}$$

Algorithm 1 Re-Aim Control of p_i

```
$minD = \infty$;
$angle_1 = -A_i$;
while $angle_1 \leq A_i$ do
    $angle_2 = -A_i$;
    while $angle_2 \leq A_i$ do
        $\phi = \phi_i(K) + angle_1$;
        $\theta = \theta_i(K) + angle_2$;
        Derive $\hat{Z}_i$, which is the point detected by $p_i$ using the angle commands $\phi$ and $\theta$;
        if $\|(\hat{Z}_i - \hat{Z}_1)\| < minD$ then
            $minD = \|(\hat{Z}_i - \hat{Z}_1)\|$;
            $store_1 = angle_1$;
            $store_2 = angle_2$;
        end if
        $angle_2 = angle_2 + minA$;
    end while
    $angle_1 = angle_1 + minA$;
end while
Aim the laser $p_i$ at yaw angle $\phi = \phi_i(K) + store_1$;
Aim the laser $p_i$ at pitch angle $\theta = \theta_i(K) + store_2$;
```

Suppose that all lasers are re-aimed at the the identical aiming point, say $\hat{Z}$. Once a laser of p_i aims at the aiming point $\hat{Z}$, then the laser is fired at $\hat{Z}$.

In Algorithm 1, one derives $\hat{Z}_i$ (aiming point for p_i) while $angle_1$ and $angle_2$ change $\frac{2*A_i}{minA}$ times, respectively. In total, one derives $\hat{Z}_i$ while the laser direction angle changes $\frac{(2*A_i)^2}{(minA)^2}$ times. This implies that the computational load of Algorithm 1 is $O(\frac{(2*A_i)^2}{(minA)^2})$.

In MATLAB simulations, one assumes that this angle change in Algorithm 1 can be done within one sampling interval dt. It is argued that if fast mirrors are used, very fast angular velocities can be realised. Thus, a moving target can be considered as a static aerial target within one sampling interval.

III. MATLAB SIMULATIONS

One verifies the effectiveness of the proposed multi-laser systems using MATLAB simulations. Simulation settings are as follows. In Algorithm 1, one sets $minA = 0.01$ degree, which is feasible according to [15]. In (12), one sets $\zeta = 2$ meter.

In simulations, a laser has a beam diameter of 0.1 meter [4] and is collimated at the target position. The beam profile is assumed to be Gaussian [16]. Considering the coherence length of laser, one has integrated the beam intensity of every laser system at target space.

One considers the case where five high power lasers are fired at the target simultaneously. To simulate the detection error of multiple lasers, one generates $\hat{Z}_i$ (aiming point for p_i) as follows.

$$\hat{Z}_i = \hat{Z}_1 + n_i. \tag{19}$$

Here, n_i is a Gaussian noise with mean 0 and covariance $\zeta^2 * I_3 * eye(3)$. Here, $eye(3)$ denotes an identity matrix with size 3 by 3. Due to the random noise n_i, all lasers are not aimed accurately. In (19), n_i is set, considering stochastic influences of engineering factors such as aiming precision/source radial stability, or optical path variation due to turbulence (or blooming).

Consider a military scenario where multiple high power laser weapon systems are positioned closed to a base, in order to protect the base from an incoming target. Suppose that the base is located at the origin. The aerial target is located at [0, 1000, 1000] in meters. Every laser system is located at [0,0,0], [D,0,0], [−D,0,0], [0,−D,0], and [0,D,0] respectively.

A. THE RE-AIM STRATEGY IS NOT USED

To verify the effectiveness of the re-aim strategy (Algorithm 1) in Section II-C3, one first considers the case where the re-aim strategy is not applied.

First, consider the case where one sets $D = 5$ m. In Fig. 3, one considers the local frame centered at the target point, which is located at [0, 1000, 1000] in meters. The intensity in each plane (*xy,xz,yz*) is depicted in Fig. 3. The intensity is not sufficiently aimed, as depicted in Fig. 3. The figure shows that lasers are not aimed accurately.

Next, one considers the case where one sets $D = 500$ m. In Fig. 4, one considers the local frame centered at the target point. The intensity in each plane (*xy,xz,yz*) is depicted in Fig. 4. The intensity is not sufficiently aimed.

B. THE RE-AIM STRATEGY IS USED

One next applies the re-aim strategy (Algorithm 1) in Section II-C3 at the five lasers.

Consider the case where one sets $D = 5$ m. Under the re-aim strategy (Algorithm 1) in Section II-C3, the beam intensity in each plane (*xy,xz,yz*) is depicted in Fig. 5. Compared to Fig. 3, it is clearly shown that by applying the re-aim strategy (Algorithm 1) in Section II-C3, the beam intensity increases considerably. See the right colorbar. This is due to the fact that five lasers are focused under the re-aim strategy (Algorithm 1).

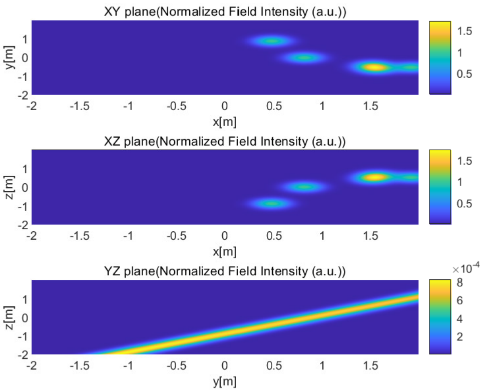

FIGURE 3. One sets $D = 5$ m. Field intensity of five lasers, while the re-aim strategy (Algorithm 1) in Section II-C3 is not applied. This figure shows the beam intensity in each plane (*xy,xz,yz*). The intensity is not sufficiently aimed.

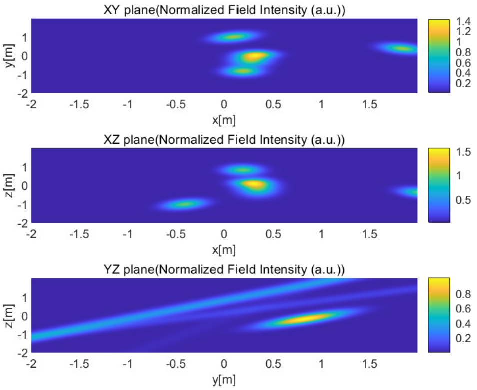

FIGURE 4. One sets $D = 500$ m. Field intensity of five lasers, while the re-aim strategy in Section II-C3 is not applied. This figure shows the beam intensity in each plane (*xy,xz,yz*). The intensity is not sufficiently aimed.

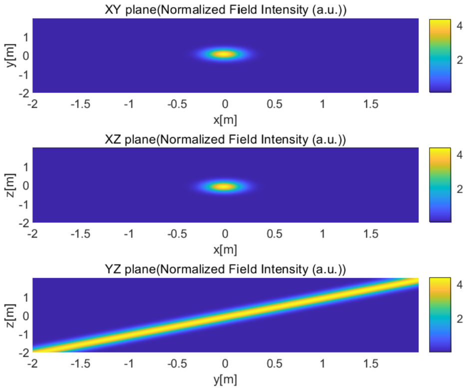

FIGURE 5. One sets $D = 5$ m. Field intensity of five lasers, while the re-aim strategy (Algorithm 1) in Section II-C3 is applied. This figure shows the beam intensity in each plane (*xy,xz,yz*). Compared to Fig. 3, it is clearly shown that by applying the re-aim strategy (Algorithm 1), the beam intensity increases considerably. See the right colorbar. This is due to the fact that five lasers are focused under the re-aim strategy (Algorithm 1).

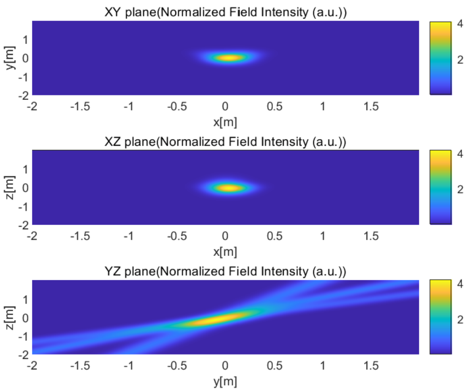

FIGURE 6. One sets $D = 500$ m. Field intensity of five lasers, while the re-aim strategy (Algorithm 1) is applied. This figure shows the beam intensity in each plane (*xy,xz,yz*). Compared to Fig. 4, it is clearly shown that by applying the re-aim strategy (Algorithm 1), the beam intensity increases considerably. See the right colorbar. This is due to the fact that five lasers are focused under the re-aim strategy (Algorithm 1).

Next, consider the case where one sets $D = 500$ m. Under the re-aim strategy (Algorithm 1), the beam intensity in each plane (*xy,xz,yz*) is depicted in Fig. 6. Compared to Fig. 4, it is clearly shown that by applying the re-aim strategy (Algorithm 1), the beam intensity increases considerably. See the right colorbar. This is due to the fact that five lasers are focused under the re-aim strategy (Algorithm 1).

IV. CONCLUSION

Consider a military scenario where multiple high power laser weapon systems are positioned closed to a base, in order to protect the base from an incoming target. This paper considers destroying a short-range target which is sufficiently close to the base. Multiple high power laser systems are used to destroy a short-range target.

This paper shows that using multiple lasers, one can handle the case where obstacles block the LOS path to the target, or the case where the target has a defense system in a specific direction or for a specific region. This paper presents how to make multiple high power lasers aim at a single point of the target to maximize the attack efficiency. This paper further addresses how to make every laser aim at a single target point with the maximum allowable speed. The re-aiming control method is further proposed to compensate for the detection error of multiple lasers. The efficiency of the proposed methods has been verified via numerical simulations.

This paper forms the basis of precise control for multi-laser systems. As our future works, one will verify the performance of the proposed multi-laser systems using real laser systems. By adopting adaptive optics [17], the system will be improved under atmospheric conditions or target movements. The proposed laser control systems can be used for making ground vehicles point the microwave antenna to a flying platform, so that communication can be achieved [18].

There may be a case where the target moves fast, and it is not destroyed under the proposed multi-laser control strategy. For instance, the target may be covered with reflective coatings. In this case, we re-run search radar systems for re-calculating the target's global position information. The target information is then shared by all lasers through fiber-based wired links, so that all lasers aim at the identical target point. In this way, we keep iterating the proposed multi-laser control strategy until the target is destroyed.

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