UAV_1 has lost its way to its target location and its tracking error will not be reduced anymore.

We have then our proposed MAPF method under the same set up. Figure 9 shows the trajectory of each UAV and how they generate the given formation. We can see that, at the beginning stage, all UAVs are heading to the formation area directly. When they come close enough to this area, they move around the formation center (which directly related with k_{a1}/k_{r1}) to make sure all UAVs are well distributed. Once *Phase 1*'s goal is achieved, all UAVs will move toward to the nearest target location directly.

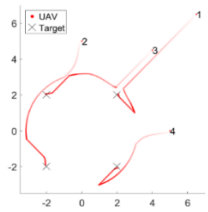

Figure 9. MAPF method formation generation

Figure 10 shows the tracking error of each UAV in both Phase 1 and Phase 2. At first, errors of all UAVs decrease quickly. After around 75 time-units, UAVs start moving around the formation center to make sure all UAVs come near to the formation area and spread well. Because of this kind of behavior, the tracking error goes up a little bit. And at the last stage, all UAVs move towards the target position as expected.

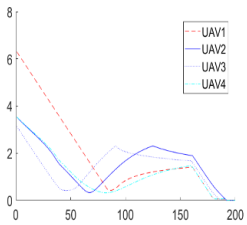

Figure 10. MAPF formation generation error

5. CONCLUSIONS

In this paper, the Modified Artificial Potential Field method has been proposed to control a group of autonomous UAVs to achieve and maintain a given formation while avoiding collisions. Unlike other centralized UAV formation control methods, the MAPF method does not require high computational capability and the flying trajectory can be modified in real time when an unexpected obstacle has been detected. The MAPF method has two phases. UAVs will be gathered around the formation center during *Phase 1* and the given formation will be achieved in *Phase 2*. Simulation results show the capability of the algorithm dealing with formation processing.

ACKNOWLEDGMENT

This work has been partially funded by the Center for Advanced Systems and Engineering (CASE) at Syracuse University and Gryphon Sensors.

REFERENCES

[1] Casbeer D.W., Li S.M., Beard R.W., McLain T.W., Mehra R.K. (2005). Forest fire monitoring using multiple small UAVs, *American Control Conference*, Vol. 5, pp. 3530-3535.

[2] Maithripala D.H.A., Jayasuriya S. (2005). Radar deception through phantom track generation, *ACC*, DOI: 10.1109/ACC.2005.1470620

[3] Khatib O. (1986). Real-time obstacle avoidance for manipulators and mobile robots, *The International Journal of Robotics Research*, Vol. 5, No. 1, pp. 90-98. DOI: 10.1177/027836498600500106

[4] Laumond J.P. (1998). Robot motion planning and control, Springer. DOI: 10.1007/BFb0036069

[5] Hussien B. (1989). Robot path planning and obstacle avoidance by means of potential function method, Ph. D Dissertation, University of Missouri-Columbia, USA.

[6] Ge S.S., Cui Y.J. (2000). New potential functions for mobile robot path planning, *IEEE Transactions on Robotics and Automation*, Vol. 16, No. 5, pp. 615-620. DOI: 10.1109/70.880813

[7] Yang Y., Wang S., Wu Z., Wang Y. (2011). Motion planning for multi-HUG formation in an environment with obstacles, *Ocean Engineering*, Vol. 38, No. 17, pp. 2262-2269. DOI: 10.1016/j.oceaneng.2011.10.008

[8] Asl A.N., Menhaj M.B., Sajedin A. (2014). Control of leader-follower formation and path planning of mobile robots using Asexual Reproduction Optimization (ARO), *Applied Soft Computing*, Vol. 14, pp. 563-576.

[9] Liu X., Ge S.S., Goh C.H. (2016). Formation potential field for trajectory tracking control of multi-agentsin constrained space, *International Journal of Control*, pp. 1-15.

[10] Wei E., Li T., Hu Y. (2013). Robust adaptive neural network control for wheeled inverted pendulum with input saturation, *10th International Symposium on Neural Networks*, Dalian. DOI: 10.1007/978-3-642-39068-5_6

[11] Ge S.S., Liu X., Goh C.H., Xu L. (2015). Formation tracking control multi-agents in constrained space, *IEEE Transactions on Control Systems Technology*, Vol. 24, No. 3, pp. 992-1003.

[12] Chen M., Ge S.S., Choo Y.S. (2009). Neural network tracking control of ocean surface vessels with input saturation, *The IEEE International Conference on Automation and Logistics*, Shenyang, China. DOI: 10.1109/ICAL.2009.5262972

[13] Ma H., Wang M., Jia Z., Yang C. (2011). A new framework of optimal multi-robot formation, *30th Chinese Control Conference*.

[14] Wang X., Yadav V., Balakrishanan S.N. (2007). Cooperative UAV formation flying with obstacle/collision avoidance, *IEEE Transactions on Control System Technology*, Vol. 15, No. 4, pp. 672-679. DOI: 10.1109/TCST.2007.899191

[15] Luo G., Yu J., Mei Y., Zhang S. (2015). UAV path planning in mixed-obstacle environment via artificial potential field method improved by additional control force, *Asian Journal of Control*, Vol. 17, No. 5, pp. 1600-1610.