REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
01-09-2009	Final Report	1-Aug-2006 - 30-Nov-2009

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Development of Adaptive Algorithms for Visual Control of Autonomous Multi-Vehicle Systems	W911NF-06-1-0330
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102
6. AUTHORS Naira Hovakimyan	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Virginia Polytechnic Institute & State University Office of Sponsored Programs Virginia Polytechnic Institute and State University Blacksburg, VA 24060 -	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 49447-NS.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

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14. ABSTRACT

This grant developed guidance and control algorithms for coordination of multiple vehicles in uncertain adversarial environments. Particular emphasis was on the use of vision-based sensors. The particular objectives were motivated by various mission scenarios that a system of autonomous vehicles might need to accomplish. Examples include intelligent surveillance and reconnaissance (ISR), ground target suppression, sequential autolanding, search and rescue, etc.

15. SUBJECT TERMS

vision-based control, autonomous systems, robust adaptation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Naira Hovakimyan
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Development of Adaptive Algorithms for Visual Control of Autonomous Multi-Vehicle Systems
49447-CI (final report)

Naira Hovakimyan, University of Illinois at Urbana-Champaign

Foreword: The objective of this effort is to develop guidance and control algorithms for coordination of multiple vehicles in uncertain adversarial environments with particular emphasis on the use of vision-based sensors. This *broad* objective is related to various mission scenarios that a system of autonomous vehicles might need to accomplish. Examples include intelligent surveillance and reconnaissance (ISR), ground target suppression, sequential autolanding, search and rescue, etc.

Statement of the Problem: We consider the problem of steering a fleet of UAVs, equipped with commercial off-the-shelf autopilots and monocular cameras with complementary visual capabilities (resolution), along the given paths (path following) under strict spatial and/or temporal constraints (collision-free, simultaneous arriving, etc.). The UAV with high resolution fixed camera is used to find and recognize the ground target moving with time-varying velocity. After the target is recognized, the UAV with low resolution gimbaled camera switches to tracking mode, and maintains a desired ground distance from the moving target, while the high resolution UAV lowers down the altitude and takes video of the target, still coordinating with the tracking UAV.

Towards this objective, our initial approach during the first year of the grant was to develop basic fundamental theory for coordination of multi-vehicle systems in the presence of spatial constraints with guaranteed performance bounds, assuming that the inter-vehicle communication network topology is fixed in time. In particular, we have demonstrated how the L1 adaptive control theory can be used for augmentation of the off-the-shelf autopilots to enable time-critical coordination within spatial constraints – missions that these autopilots were not originally designed to perform. During the second year we extended the theoretical framework to allow for time-varying communication network topology, including network failures and delays. Leveraging from our basic research performed under AFOSR grant, we proved that the L1 adaptive control theory can be used to ensure uniform performance bounds and accurate path following for a fleet of vehicles in the presence of time-varying inter-vehicle communication network topology. During the second year, we also explored reactive vision-based obstacle avoidance algorithms for vehicles following a given path. During the third year, we developed the vision-based ground target tracking and motion estimation algorithm using a single UAV equipped with a gimbaled camera. The estimator for target position and velocity is a *fast estimator* and has guaranteed estimation error bound, which makes it possible to use the target image (vision) as feedback and reduce the dependence on GPS. The accurate estimation of the target motion also allows for extension of the previously designed tracking algorithm from the case of static target to the case of moving target with time-varying velocity.

Our next step will be to flight test these algorithms jointly with NPS, using their small UAVs, leveraging additional sources of funding for that (e.g. a joint grant with NPS from ONR under 6.2 portfolio).

Summary of the Main Results: We develop *verifiable* robust adaptive control algorithms that can compensate for rapidly varying uncertainties without losing robustness. The architectures of *L1 adaptive control theory* allow for *a priori* quantification of the performance bounds and analytical computation of robustness/stability margins. These architectures have uniformly bounded transient performance for systems both signals, input and output, simultaneously.

In collaboration with I. Kaminer from NPS, we have demonstrated:
1. Augmentation of the off-the-shelf autopilots to enable accurate path following and, further, time-critical coordination with aggressive 3D path following of multiple UAVs subject to spatial constraints in the presence of time-varying inter-vehicle communication network topology – missions that these autopilots were not originally designed to perform,
2. Target motion estimation with estimation error that can be rendered arbitrarily small – the key step towards enabling vision-based target tracking, motion estimation, and accurate path following.
3. Vision-based target tracking using L1 adaptation in both loops for estimation and feedback to enable accurate tracking of moving target with time-varying velocity.

These architectures are being flight tested by I. Kaminer in TNT exercises at Camp Roberts, CA, supported by USSOCOM. Further, there is a transition effort at place via ONR funding.

***Memo**:* We have presented some of our preliminary results in ARLs in Picatinny Arsenal and Aberdeen Proving Grounds.

Accomplishments

- Augmentation of existing autopilots for coordinated path following of multiple UAVs over time varying communication networks subject to spatial and temporal constraints, flight tested by I. Kaminer from NPS, in Camp Roberts, CA, in February of 2007.
- Fast adaptive motion estimation and vision-based target tracking using single UAV with gimbaled camera.
- Coordination of two UAVs, equipped with monocular cameras, for tracking a moving target with time-varying velocity (to be flight tested in October 2009 by NPS, leveraging additional sources of funding for that, e.g. ONR).
- Visiting Army Labs in Aberdeen Proving Grounds, MD, and Picatinny Arsenal, NJ, for opportunities of transitioning the technology.

Collaborations and Leveraged Funding: We have developed collaboration with Prof. I. Kaminer from NPS under joint ONR grants. I. Kaminer is funded by USSOCOM (US Special Ops Command) SORSE (Special Operations Research and Support Element). We also have a joint grant with Isaac Kaminer from NASA under the NRA program on flight test validation of metrics driven adaptive control. Currently we are also funded by ONR to develop a flight test program, which would use the theoretical solutions developed under this grant. There is further interest from ONR in supporting these solutions from their 6.2 funding portfolio with an objective of transitioning it into Navy technology.

Technology Transfer: As mentioned above, these algorithms have been flight tested on I. Kaminer's testbeds from NPS, which is a governmental lab. These are being further transitioned to USSOCOM (US Special Ops Command) by him on a quarterly basis during the TNT exercises in Camp Roberts, CA. I. Kaminer's contact is kaminer@nps.edu, (831) 656-3459. He can provide further details on this. Other technology transfers of basic fundamental research include WP AFRL/Boeing CerTA FCS CPI program (X-48B), NASA IRAC program (GTM AirSTAR) and Raytheon Co. NASA Dryden is planning to integrate the methodology in F-18.

Publications:

Journals:

1. V. Stepanyan, N. Hovakimyan, An Adaptive Disturbance Rejection Controller for Visual Tracking of a Maneuvering Target, AIAA Journal of Guidance, Control and Dynamics, vol. 30, No. 4, pp. 1090-1106, 2007.

2. V. Stepanyan, N. Hovakimyan, Visual Tracking of a Maneuvering Target, AIAA Journal of Guidance, Control and Dynamics, vol. 31, No. 1, pp. 66-80, 2008.

3. C. Cao, N. Hovakimyan, Vision-based Tracking using Intelligent Excitation, International Journal of Control, vol. 81, No.11, pp. 1763-1778, 2008.

4. C. Cao, N. Hovakimyan, J. Evers, Active Control of Visual Sensor for Aerial Tracking, Journal of Computational Management Science, Springer Operation Research and Decision Theory, 2008.

5. A. Young-Dippold, L. Ma, N. Hovakimyan, Vision-Based Obstacle Avoidance of Wheeled Robots Using Fast Estimation, AIAA Journal of Guidance, Control and Dynamics, vol. 33, 2010.

6. L. Ma, C. Cao, N. Hovakimyan, C. Woolsey, W. Dixon, Fast Estimation for Range Identification in the Presence of Unknown Motion Parameters, Submitted to IMA Journal of Applied Mathematics, 2008.

7. I. Kaminer, A. Pascoal, E. Xargay, C. Cao, N. Hovakimyan, V. Dobrokhodov, 3D Path Following for Small UAVs using Commercial Autopilots Augmented by L1 Adaptive Control, Submitted to AIAA Journal of Guidance, Control and Dynamics, 2009.

Conferences:

1. C. Cao, N. Hovakimyan, I. Kaminer, V. Patel, V. Dobrokhodov, Stabilization of Cascaded Systems via L1 Adaptive Controller with Application to a UAV Path Following Problem and Flight Test Results, In Proceedings of American Control Conference, New York, NY, pp. 1787-1792, 2007.

2. L. Ma, C. Cao, N. Hovakimyan, W. Dixon, C. Woolsey, Range Identification in the Presence of Unknown Motion Parameters for Perspective Vision Systems, In Proceedings of American Control Conference, New York, NY, pp. 972-977, 2007.

3. I. Kaminer, N. Hovakimyan, V. Patel, C. Cao, A. Young, A. Pascoal, Time-Critical Coordinated Path Following for Multiple UAVs via L1 Adaptive Output Feedback Controllers, In Proceedings of European Control Conference, Kos, Greece, 2007.

4. L. Ma, C. Cao, N. Hovakimyan, Fast Estimation for Range Identification in the Presence of Unknown Motion Parameters, In Proceedings of International Conference on Informatics in Control, Automation & Robotics, Angers, France, 2007.

5. L. Ma, C. Cao, N. Hovakimyan, C. Woolsey, V. Dohrokhodov, I. Kaminer, Development of a Vision-Based Guidance Law for Tracking a Moving Target with Time-Varying Velocity, AIAA-2007-6744, In Proceedings of AIAA Guidance, Navigation and Control Conference, Hilton Head Island, SC, 2007.

6. V. Dohrokhodov, I. Kaminer, K. Jones, I. Kitsios, C. Cao, L. Ma, N. Hovakimyan, C. Woolsey, Rapid Motion Estimation of a Target Moving with Time-Varying Velocity, AIAA-2007-6746, In Proceedings of AIAA Guidance, Navigation and Control Conference, Hilton Head Island, SC, 2007.

7. I. Kaminer, O. Yakimenko, V. Dohrokhodov, A. Pascoal, N. Hovakimyan, C. Cao, A. Young, V. Patel, Coordinated Path Following for Time-Critical Missions of Multiple UAVs via Adaptive Output Feedback Controllers, AIAA 2007-6409, In Proceedings of AIAA Guidance, Navigation and Control Conference, Hilton Head Island, SC, 2007.

8. P. Aguiar, I. Kaminer, R. Ghabcheloo, A. Pascoal, E. Xargay, N. Hovakimyan, C. Cao, Coordinated Path Following of Multiple UAVs for Time-Critical Missions in the Presence of Time-Varying Communication Topologies, IFAC Congress, Seoul, South Korea, 2008.

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10. L. Ma, C. Cao, N. Hovakimyan, V. Dobrokhodov, I. Kaminer, Adaptive Vision-Based Guidance Law with Guaranteed Performance Bounds for Tracking a Ground Target with Time-Varying Velocity, AIAA-2008-7445, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.

11. L. Ma, C. Cao, A. Young, N. Hovakimyan, Motion Estimation via a Zoom Camera, AIAA-2008-7446, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.

12. A. Young, L. Ma, N. Hovakimyan, Vision-Based Obstacle Avoidance of Wheeled Robots using Fast Estimation, AIAA-2008-7449, AIAA Guidance, Navigation and Control Conference, Honolulu, HI, 2008.

13. L. Ma, C. Cao, N. Hovakimyan, C. Woolsey, G. Hu, Estimation of Affine Motion, American Control Conference, St. Louis, MO, 2009.

14. Z. Li, V. Dobrokhodov, N. Hovakimyan, I. Kaminer, Development and Implementation of L1 Adaptive Gimbal Tracking Loop Onboard of Small UAV, AIAA-2009-5681, AIAA Guidance, Navigation and Control Conference, Chicago, IL, 2009.

Honors and Awards:

2009 Plenary talk, IASTED Conference on Identification and Control, Honolulu, HI

2008 Schaller faculty scholar at UIUC

2008 Outstanding reviewer for AIAA Journal of Guidance, Control and Dynamics

2008 Golden Screw Award, bestowed by Virginia Tech aerospace and ocean engineering outgoing seniors

2008 Dean’s Award for Research Excellence, Virginia Tech

2008 Certificate for Distinguished Service to AIAA Guidance, Navigation and Control Technical Committee (2004-2008)

2007 Plenary Speaker, SIAM Conference on Control and Its Applications (CT07), San Francisco, CA

2006 College of Engineering Faculty Fellow, Virginia Tech

2004, 2005, 2007 Recipient of Pride@Boeing Award

2000, 2006, 2007 Best Presentation Award, American Control Conference